Market Analysis of Emerging Electric Energy Storage Systems

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Final Report

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Disclaimer

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Executive Summary

Unlike markets for storable commodities, electricity markets depend on the real-time balance of supply and demand. Although much of the present-day grid operates effectively without storage, cost-effective ways of storing electrical energy can help make the grid more efficient and reliable, and may help to compensate for the variability inherent in wind and solar power. This project has investigated the economics of two emerging electric energy storage (EES) technologies: sodium sulfur (NaS) batteries and flywheels in the electricity markets operated by the New York Independent System Operator (NYISO) and the PJM Interconnection (PJM).

Although it is difficult to store electricity directly, electric energy can be stored in other forms, such as potential, chemical, or kinetic energy. Advanced EES technologies based on these principles are emerging as a potential resource in supporting an efficient electricity markets. Approximately 2.5% of the total electric power delivered in the United States passes through energy storage, almost all of which is pumped hydroelectric storage. The restructuring of the electricity industry, along with increased requirements for power reliability and quality, has made utility-scale EES a subject of current interest.

This research has evaluated the economics of two emerging EES technologies, sodium sulfur (NaS) batteries for energy arbitrage and flywheel EES systems for regulation services.

Technical applications of EES include grid stabilization, grid operational support (frequency regulation services, contingency reserves, voltage support, and black start), power quality and reliability, load shifting, and compensating for the variability of renewable energy sources. Restructured electricity markets provide opportunities for EES to participate in energy arbitrage and ancillary services (regulation, operating reserves, capacity markets, and demand response).

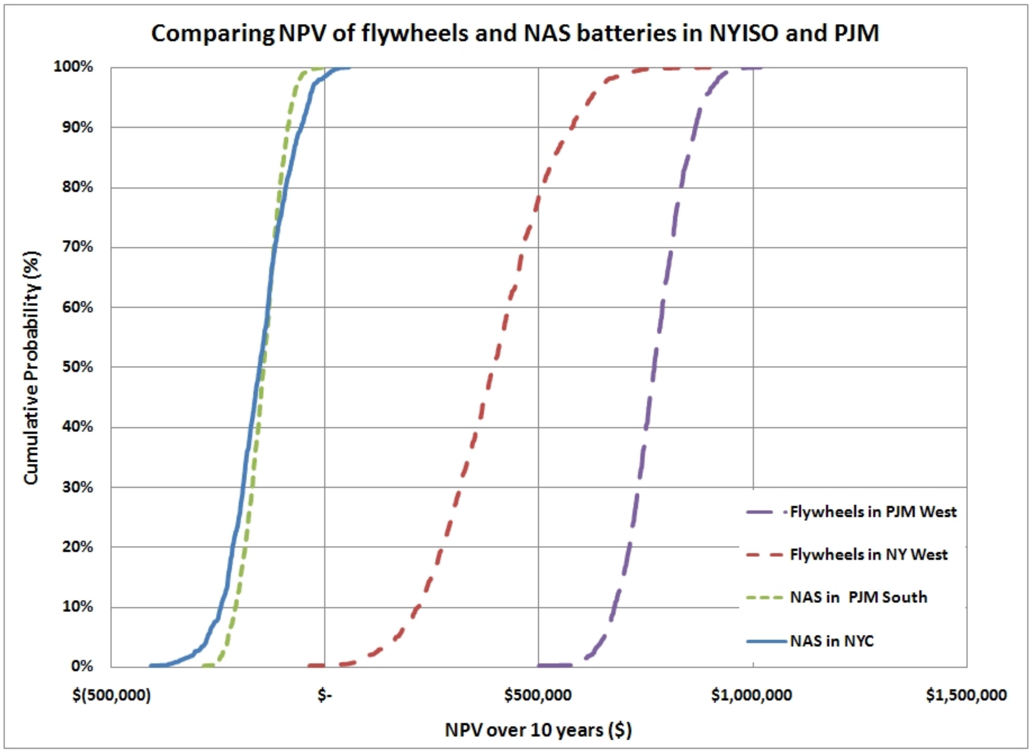
We performed market analyses of two EES technologies in the NYISO and PJM markets using historical hourly electricity market data for energy, ancillary services, and capacity (2001-07 data for NYISO and 2005-07 data for PJM). Only 2005 and later data were used for PJM to avoid systematic errors during the PJM geographic expansion between 2002-05. For both PJM and NYISO markets we evaluated revenue streams for multiple applications including 10 hour energy arbitrage, 4 hour energy arbitrage with 15 hours of synchronized reserve service, and frequency regulation. We explored the effects of the power to energy ratio as well as effect of round-trip efficiency on the choice of application from 10 hour to 2 hour energy arbitrage. We compared the economics across various regions in both ISOs.

The table below provides a summary of annual net revenues anticipated for these applications in all 7 regions across NYISO and PJM. For applications involving energy arbitrage, we have also accounted for the revenues that can be captured through capacity markets and is indicated by an asterisk in the title. Since the 15 minute duration flywheel is not eligible for such capacity revenues, the revenues considered for regulation application are only from regulation market.

	Energy Arbitrage* (10 Hrs)			Energy Arbitrage* (4Hrs)			Energy Arbitrage* (4 Hrs) + Synch Reserve (15 Hrs)			Regulation (24 Hrs)		
Region	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
NY West	$ 22	$ 35	$ 44	$ 34	$ 49	$ 62	$ 46	$ 75	$102	$ 75	$222	$401
NY East	$ 26	$ 47	$ 66	$ 41	$ 58	$ 74	$ 57	$ 89	$125	$ 67	$212	$389
NYC	$ 91	$150	$192	$ 96	$157	$202	$112	$189	$254	$ 59	$201	$371
PJM West	$ 44	$ 78	$ 90	$ 50	$ 83	$ 93	$ 53	$ 96	$127	$219	$276	$389
PJM Central	$ 43	$ 78	$118	$ 52	$ 87	$126	$ 91	$138	$188	$213	$266	$346
PJM East	$ 89	$116	$141	$100	$127	$145	$140	$177	$207	$205	$255	$333
PJM South	$103	$124	$152	$116	$135	$156	$155	$185	$218	$201	$252	$332

The analysis indicates that 4 hour energy arbitrage with 15 hours of synchronized reserve application provides the highest net revenues for NaS batteries. These are highest in the New York City (NYC) region in NYISO and in the PJM South region in PJM. Since regulation revenues are the same across the ISO territories, a flywheel can receive the highest net revenues in NY West in NYISO and PJM West in PJM, due to lower energy costs for the round-trip and standby losses in these regions.

We performed Monte Carlo simulations using market data to study the effect of capital cost, round-trip efficiency, and location on the distribution of net present value (NPV) for each system. This simulation was performed for 1,000 iterations using a triangular distribution for the net revenue for various applications discussed above. The base case analysis used a capital cost estimate of $1500/kW for a flywheel system with round-trip efficiency of 85% and $2000/kW for NaS batteries with a round-trip efficiency of 75%. We note that an annual benefit of $100,000 to $150,000 is reported by industry sources for power quality or T&D upgrade deferral benefits based on existing literature. The figure below shows the cumulative probability distributions for NaS batteries and flywheels in PJM and NYISO markets.



The analysis indicates that for the base case scenario there is over a 98% probability that a NaS battery will have a negative NPV in both NYISO and PJM. However, the analysis for flywheel systems shows a 100% probability of positive NPV in both NYISO and PJM. Some of the uncertainties regarding regulation market rules such as allocation of opportunity costs and the effects of the energy limited nature of flywheels on future compliance rules may explain the current lack of investment in flywheels. On the other hand, some market participants have made investments in NaS batteries due to anticipated system upgrade deferral benefits. Capital cost reduction and efficiency improvements are factors that will influence the economics of NaS batteries for energy arbitrage in deregulated electricity markets.

The increasing penetration of variable renewable generators in the electricity grid could enhance the economics of future EES projects. NYISO is anticipating over 3000 MW of wind being added to the grid by 2012. Although this represents approximately 10% of the peak load for NYISO, wind could contribute to 20-30% of the off peak energy requirements due to lower system loads at night. This may result in downward pressure on off peak electricity prices, thus improving the economics of energy arbitrage. In addition, the variability of wind could result in an increased requirement for ancillary services, increasing revenues for EES for ancillary services including regulation and operating reserves.

Our analysis indicates that, although current policies allow emerging EES technologies to participate in energy markets for capturing energy arbitrage opportunities, changes in some of the ancillary service-related policies can reduce financial and regulatory uncertainty for EES. While the primary barriers to EES penetration are economic, in both PJM and NYISO changes to current market rules and reliability criteria could permit EES to participate in the synchronous spinning reserve market and reduce the current uncertainty in regulation market rules.

- Market rules should be changed to resolve uncertainty related to the energy limited nature of EES in regulation markets. NYISO is currently considering a rule change that would mandate a response rate of greater than 90% from regulation units, which could result in disqualification of energy limited EES such as flywheels (which may have as much as 40% idle time based on the nature of the regulation signal). If adopted, this rule would inhibit the adoption of flywheels. The market rules for regulation should recognize the limited energy availability as well as faster response time provided by energy storage technologies. This would require that the regulation signal sent to these devices be customized to ensure that units such as flywheels are not sitting idle due to their energy limited nature. The California ISO is currently evaluating such an option to introduce a separate category of regulation services through fast response energy storage technologies.

- Our analysis indicates that the case for EES to participate in regulation market could be further enhanced if the opportunity costs paid to traditional generators are captured as part of the regulation market clearing price (RMCP) in PJM. PJM is considering changes to the RMCP payment that may include EES.

- The current market rules related to synchronized reserves permit that the service can be provided by generators synchronized to the grid operating on no load. Thus although EES can meet the technical requirements of synchronized reserves, the market rules should ensure that EES is eligible to receive synchronous reserve payments, by making reserve payments technology independent. PJM has already modified market rules to allow demand response participation in the ancillary service markets and NYISO is currently working on similar modifications; EES should receive similar consideration.

Our analysis also indicates that EES R&D efforts should focus on both improving the round-trip efficiency and reducing capital cost.

1: Overview of Emerging Energy Storage Technologies in Deregulated Electricity Markets

1-1. Introduction

Although the present-day electric grid operates effectively without storage, cost-effective ways of storing electrical energy can help make the grid more efficient and reliable. Electric energy storage (EES) can be used to accumulate excess electricity generated at off-peak hours and discharge it at peak hours. This application could yield significant benefits including a reduced need for peak generation (particularly from expensive peaking plants) and reduced strain on transmission and distribution networks. EES can also provide critically important ancillary services such as grid frequency regulation, voltage support, and operating reserves, thereby enhancing grid stability and reliability.

The term EES as used in this report refers specifically to the capability of storing energy that has already been generated as electricity and controllably releasing it for use at another time (EPRI, 2003). Although it is difficult to store electricity directly, electric energy can be stored in other forms, such as potential, chemical, or kinetic energy. Advanced EES technologies based on these principles are emerging as a potential resource in supporting an efficient electricity market. In general, large-scale applications of EES have been limited in the utility industry. Utility-scale EES projects based on storage technologies other than pumped hydroelectric storage have been built, though they have not become common. Existing US facilities include one compressed air energy storage (CAES) system, several plants based on lead-acid batteries, and one based on nickel-cadmium batteries. In all, roughly 2.5% of the total electric power delivered in the United States passes through energy storage, largely pumped hydroelectric. The percentages are somewhat larger in Europe and Japan, at 10% and 15%, respectively (EPRI, 2003).

The restructuring of the electricity industry, along with increased requirements for power reliability and quality has made utility-scale EES more attractive. This has stimulated research and development of a number of new EES technologies. Representative technologies include redox flow batteries (Bartolozzi, 1989; Price, 2000), sodium-sulfur batteries (Oshima et al., 2005), lead-acid batteries (EPRI, 2003), flywheels (Lazarewicz, 2005), pumped hydroelectric storage (Perekhodtsev, 2004), and compressed air energy storage (CAES) (DeCarolis and Keith, 2006). Battery and flywheel technologies are geographically less constrained than hydroelectric storage or CAES.

1-2. Review of Emerging EES Technologies

EES technologies can be grouped as electrochemical and non-electrochemical EES technologies. The most common EES technologies are:

- **Electrochemical EES**
    - Lead Acid Battery
    - Sodium-Sulfur battery (NaS)

- Flow Batteries
  - Vanadium Redox Battery (VRB)
  - Zinc Bromine Battery (ZnBr)
- Nickel Cadmium (NiCd) Battery
- Nickel Metal Hydride (NiMh) Battery
- Lithium Ion (Li-ion) Battery

- **Non-Electrochemical EES**
  - Pumped Hydroelectric
  - Compressed Air Energy Storage (CAES)
  - Flywheel
  - Ultra-Capacitor
  - Superconducting Magnetic Energy Storage (SMES)

The EES technologies listed above are described in detail in EPRI (2003, 2004) and Gyuk et al. (2005). Although all of these technologies are viable for utility-scale systems, some are believed to have more potential than others, as discussed below. Appendix 1-A provides a summary comparison of various EES technologies.

This research has evaluated the economics of two emerging EES technologies, sodium sulfur (NaS) batteries for energy arbitrage and flywheel EES systems for regulation services. We considered several factors in selecting technologies for market analysis. First, very large-scale storage such as pumped hydro and CAES continue to have potential where geographic considerations and other factors such as public acceptance allow their use. In New York State, most suitable pumped hydro sites have already been developed. Most prospective CAES sites are in western New York, where the economic case for energy storage is the weakest (Walawalkar et al. 2005), as discussed in Section 2. Second, lead-acid batteries were not included in this analysis because utilities are reluctant to accept this technology for electric market applications due to their relatively short service life, significant environmental effects, and high maintenance costs (EPRI 2003). Flow batteries such as Zinc bromine and Vanadium Redox batteries are less economically attractive than NaS batteries due to higher capital cost and lower roundtrip efficiencies. With the currently available data, NaS batteries have the best economics among the advanced battery technologies for MW-size utility applications (EPRI, 2006). Third, the extremely high cycle life of flywheel devices make them viable solutions for applications such as frequency regulation.

Recently, some developers have proposed the use of NaS batteries for frequency regulation. Since information on effect of frequent cycling on life expectancy of the battery was not available during this study, we have not evaluated NaS batteries for regulation service. In 2008 AES tested a new type of advanced Lithium-Titanate battery from Altair Nanotechnologies for a 2 MW – 15 min battery module designed for regulation with over 90% round-trip efficiency (the round-trip efficiency as considered in this analysis is the ac-ac efficiency including the energy storage and power conversion modules, but not transformer efficiency). Ultra-capacitors and superconducting magnetic energy storage (SMES) devices, that also have excellent cycle life, may have potential in these applications, but are not yet mature enough to consider in a utility application.

The following section provides an overview of NaS batteries and flywheels considered in this research:

1-2-1. Sodium-Sulfur Batteries

Sodium-sulfur batteries are based on a high-temperature electrochemical reaction between sodium and sulfur, separated by a beta alumina ceramic electrolyte. While originally developed for electric vehicle applications, they were adapted for the utility market by the Tokyo Electric Power Company (TEPCO) and NGK Insulators, Ltd., both based in Japan. By the late 1990s, NGK and TEPCO had deployed a series of large-scale demonstration systems, including two 6 MW, 48 MWh installations at TEPCO substations. Sodium-sulfur batteries have excellent cycle life and are relatively mature products, with over 55 installations worldwide (EPRI, 2003).

In 2002, TEPCO and NGK announced full commercialization of their sodium-sulfur battery line under the trade name NAS ®, for power quality and load shifting applications. Also in 2002, the first NaS battery was installed in the U.S. at an American Electric Power (AEP) laboratory at Gahanna, Ohio.

In 2005, the New York Power Authority (NYPA), with co-funding from Consolidated Edison, NYSERDA, the U.S. DOE, and other parties, sponsored the installation of a NaS battery rated at 1.2 MW and 7.2 MWh, for peak demand reduction and backup power at a Long Island Bus Company refueling station. AEP also installed a NaS battery at a substation near Charleston, West Virginia. This unit, also rated at 1.2 MW and 7.2 MWh, is designed to defer upgrades to the substation for six to seven years, allowing a significant reduction in capital expense. (Nourai, 2006) Both installations were completed in 2006. AEP is currently working on projects to add 6 MW of additional NaS batteries during 2008 with focus on transmission and distribution (T&D) upgrade deferral and wind integration. AEP has set a goal of having 1,000 MW of advanced storage capacity on its system in the next decade (AEP, 2007). Excel energy also announced a demonstration project to store wind energy using a 1MW NaS battery in Luverne, Minnesota.

Figure 1-1. AEP's NaS Installation (Nourai, 2006)

1-2-2. Flywheel Energy Storage

Flywheels store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor with the input of electrical energy; during discharge, the same motor acts as a generator, producing electricity from the rotational energy of the flywheel. Most products are capable of several hundred thousand full charge-discharge cycles and enjoy much better cycle life than batteries. They are capable of very high cycle efficiencies of over 90% (Lazarewicz, 2005). Since the energy sizing of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator, power and energy can be sized independently. The disadvantage of flywheels is their relatively poor energy density and large standby losses. Beacon Power Corporation is currently testing flywheels for frequency regulation applications at the transmission level in New York and California (Gyuk et al., 2005; Lazarewicz, 2005). The Beacon Power flywheels are constructed of carbon and fiberglass composites to withstand up to 22,500 revolutions/min. The flywheel is housed in a vacuum sealed steel container and employs a high speed magnetic lift system to minimize friction. Flywheels are designed to shut down benignly in case of failure, and the composite material is designed to disintegrate in case of failure to avoid potential injuries. Beacon Power has also proposed that the flywheels can be installed underground to reduce safety hazards. (Lazarewicz, 2005)

More recently, flywheels have been proposed for longer duration applications. Beacon Power Corporation has proposed a 20-MW flywheel energy storage system for frequency regulation applications at the transmission level. This application is being tested at a small scale in demonstrations in New York, funded by the New York State Energy Research and Development Authority (NYSERDA), and in California, funded by the California Energy Commission (CEC)[1]. In 2007, DOE provided a grant to Beacon Power for design of the first 20 MW flywheel regulation plant. Beacon Power has also qualified for various loans from state and federal agencies to build such a plant. Beacon Power has applied to build the first plant in NYISO using 100 kW flywheel units at Stephentown, NY.

Figure 1-2. Rahul Walawalkar with the Beacon Power Flywheel Test Installation in California

[1] Source: http://www.sandia.gov/ess/About/projects.html

Table 1-1. Summary of the Technical and Cost Details for Two EES Technologies

	NaS	**Flywheel**
EES Size	1 MW (10 MWh)	1 MW (0.25 MWh)
Total Capital Cost	$1,500,000 - 3,000,000	$750,000 -2,000,000
Annual O&M Cost	$15,000 - 90,000	$20,000 - $30,000
Cycle Life	5,000 - 20,000	100,000 - 2,000,000
Service Life (years)	12 - 20	15 - 25
Footprint (SqFt/MW)	900	150

Table 1-1 summarizes the EES technical parameters and costs for NaS batteries and flywheels.

The base estimates were derived from the data available in EPRI (2003) and updated based on information from manufacturers and industry experts. The capital cost and annual operations and maintenance cost estimates have a relatively large range, as these technologies are yet to be widely commercialized, and no published data are available. For NaS batteries the cycle life (5,000 - 20,000 cycles) is sensitive to operational parameters such as depth of discharge and environmental factors, whereas for the flywheel the cycle life (100,000 - 2,000,000 cycles) is based on design specifications. The service life estimate was derived based on the cycle life and expected usage for various market applications.

1-3. Technical Benefits of Energy Storage

Emerging EES systems (beyond traditional, but geographically limited, pumped hydroelectric storage) may provide several technical benefits for utilities, power system operations, and users. The traditional applications for energy storage are described below: (EPRI, 2003, EPRI, 2004, EPRI, 2006).

1-3-1. Grid Stabilization: EES can be used to help the transmission or distribution grid return to its normal operation after a disturbance. Energy storage can be used to remedy three forms of instability: rotor angle instability; voltage instability; and frequency excursions.

1-3-2. Grid Operational Support: In addition to stabilizing the grid after disturbances, energy storage can also be used to support normal operations of the grid. Four types of support operations can be performed through the use of energy storage:

- **Frequency Regulation Services:** Energy storage can be used to inject and absorb power to maintain grid frequency in the face of fluctuations in generation and load.

- **Contingency Reserves:** At the transmission level, contingency reserve includes spinning (or synchronous) and supplemental (non-synchronous) reserve units, that provide power for up to two hours in response to a sudden loss of generation or a transmission outage.

- **Voltage Support:** Voltage support involves the injection or absorption of reactive power (VARs) into the grid to maintain system voltage within the optimal range. Energy storage systems use power-conditioning electronics to convert the power output of the storage technology to the appropriate voltage and frequency for the grid.

- **Black Start:** Black start units provide the ability to start up from a shutdown condition without support from the grid, and then energize the grid to allow other units to start up. A properly sized energy storage system can provide black start capabilities, provided it is close enough to a generator.

1-3-3. Power Quality and Reliability: EES is often used to improve power quality and reliability. The vast majority of grid-related power quality events are voltage sags and interruptions with durations of less than 2 seconds, phenomena that lend themselves to energy storage-based solutions (EPRI 1998).

1-3-4. Load Shifting: Load shifting is achieved by utilizing EES for storage of energy during periods of low demand and releasing the stored energy during periods of high demand. Load shifting comes in several different forms; the most common is peak shaving (EPRI 2003). Peak shaving describes the use of energy storage to reduce peak demand in an area. It is usually proposed when the peak demand for a system is much higher than the average load, and when the peak demand occurs relatively rarely. Peak shaving allows a utility to defer the investment required to upgrade the capacity of the network. The economic viability of energy storage for peak shaving depends on a number of factors, particularly the rate of load growth (EPRI 2003). The $/kW cost of a distribution upgrade is usually much lower than the $/kW cost of energy storage. But the total cost of a distribution upgrade is usually much higher than the total cost of an EES optimized for deferral of a distribution upgrade for two to five years. AEP has justified the installation of NaS battery in Charleston, WV, for peak shaving based on savings from deferring the upgrade of a substation (Nourai, 2006).

1-3-5. Supporting the Integration of Intermittent Renewable Energy Sources: Wind power generation is presently the largest and fastest growing renewable power source. The following applications are described in the context of wind power (EPRI 2004). Similar applications also exist for renewable energy sources other than wind power, such as solar photovoltaic (PV).

- **Frequency and synchronous spinning reserve support:** In grids with a significant share of wind generation, intermittency and variability in wind generation output due to sudden shifts in wind patterns can lead to significant imbalances between generation and load that in turn result in shifts in grid frequency. Such imbalances are usually handled by spinning reserve at the transmission level, but energy storage can provide prompt response to such imbalances without the emissions related to most conventional solutions.

- **Transmission Curtailment Reduction:** Wind power generation is often located in remote areas that are poorly served by transmission and distribution systems. As a result, sometimes wind operators are asked to curtail their production, which results in lost energy production opportunity, or system operators are required to invest in expanding the transmission capability. An EES unit located close to the wind generation can allow the excess energy to be stored and then delivered at times when the transmission system is not congested.

- **Time Shifting:** Wind turbines are considered as non-dispatchable resources. EES can be used to store energy generated during periods of low demand and deliver it during periods of high demand. When applied to wind generation, this application is sometimes called "firming and shaping" because it changes the power profile of the wind to allow greater control over dispatch.

1-4. Information on Recent U.S. Initiatives

Currently, the U.S. Department of Energy (DOE) has two major initiatives to support development and integration of EES for electricity grid-related applications in association with the New York State Electric Research and Development Authority (NYSERDA) and the California Energy Commission (CEC). Details of these initiatives developed to demonstrate EES as a technically viable, cost-effective, and broadly applicable option for increasing the reliability and electric energy management of the electricity system are provided below:[2]

1-4-1. CEC/DOE Collaboration on Energy Storage: This collaboration is a partnership between the DOE Energy Storage Systems (ESS) Program and the CEC. In response to a CEC Program Opportunity Notice, three major projects totaling $9.6M were selected in 2005. DOE, through Sandia National Laboratories, oversees the technical management of these demonstration projects.

- A ZBB flow battery installed at a Pacific Gas & Electric substation to mitigate distribution congestion, provide voltage support, and reduce peak loads in the distribution system transformer. This demonstration project utilizes a zinc bromine battery storage system installed at an electric utility distribution substation. The objective is to defer a substation transformer upgrade until all associated planning and permitting can be accomplished.

- A Beacon Flywheel Energy Storage System (FESS) to demonstrate the feasibility of using a flywheel to provide frequency regulation services to the California Independent System Operator (CaISO). This project demonstrates a flywheel energy storage system designed to respond to a regional transmission operator signal to quickly add or subtract power from the grid in a frequency regulation support mode.

- A Dynamic Stabilizer using Maxwell ultra-capacitors to provide ride through for power interruptions to critical loads and mitigate power quality problems on a wind turbine/hydro micro grid for the Palmdale Water Treatment Plant. This project will demonstrate the use of an ultra-capacitor energy storage module in support of a

[2] Source: http://www.sandia.gov/ess/About/projects.html

selection of distributed energy resources that could potentially be configured as an electric microgrid. These resources include a 950 kilowatt wind turbine, a 200 kW natural gas generator, and a 250 kW water turbine generator.

1-4-2. NYSERDA / DOE Joint Energy Storage Initiative: This initiative is a partnership between the DOE ESS Program and the NYSERDA. In response to a NYSERDA Program Opportunity Notice, six projects totaling $5.6M were selected in 2004. They include three major demonstration projects that showcase flywheel, sodium-sulfur battery, and lead-acid battery technologies.

- The Residential Energy Storage and Propane Fuel Cell Demonstration project demonstrates the use of an 11 kW, 20 kWh Gaia Power Technologies PowerTower energy storage system in conjunction with a Plug Power GenSys propane fuel cell in an edge-of-grid residential application. The demonstration consists of two parts:
- Demand reduction using the PowerTower to provide an energy boost when the user load exceeds a preset threshold.
- Demand reduction using the PlugPower propane fuel cell as a primary electricity source in conjunction with the PowerTower.
- ***Primary participants:*** Delaware County Electric Cooperative (utility), Gaia Power Technologies (equipment manufacturer), EnerNex Corporation (data acquisition and monitoring).
- The Flywheel-Based Frequency Regulation Demonstration project (FESS), located at an industrial site in Amsterdam, NY, demonstrates grid frequency regulation by utilizing a high-energy flywheel storage system that consists of seven Beacon Power flywheels that have been adapted to operate on the Niagara Mohawk distribution grid. This system is capable of providing 100 kW of power for frequency regulation and storing 25 kW of recoverable energy.
- ***Primary participants:*** Beacon Power (equipment manufacturer), NationalGrid (utility), EnerNex Corporation (data acquisition and monitoring).
- The NaS Battery Demonstration project at a Long Island bus depot facility demonstrates the use of a NaS battery system that shifts compressor peak load to off-peak capacity and provides emergency backup power. The primary application will be to supply up to 1.2 MW of power to a natural gas compressor for six to eight hours per day, seven days per week, especially during the summer peak period.
- ***Primary participants:*** ABB, Inc. (PCS Manufacturer), New York Power Authority (NYPA), NGK Insulators, Ltd. (battery manufacturer), EnerNex Corporation (data acquisition and monitoring).

1-5. Opportunities for EES Integration in Deregulated Electricity Markets

An EES unit can participate in electricity markets in a number of ways, depending on its energy storage and delivery characteristics (Schoenung et al. 1996). Despite numerous advances in EES technologies (Gyuk et al., 2005) and technical benefits offered (EPRI 2003), markets have not yet adopted EES applications other than pumped hydro on a large scale.

Initial economic studies of EES systems focused on applications for peak shaving and as capacity resources (Sobieski and Bhavaraju 1985). In recent years there has been increased attention to evaluating the economics of EES systems as backup for intermittent renewable sources. Some examples include wind and CAES (DeCarolis and Keith 2006), wind and hydro or batteries (Bathurst 2003), solar photovoltaic and batteries (Su et al. 2001; Fabjan et al. 2001). Since the emergence of deregulated electric energy markets, several studies of the economics of EES systems have appeared, including a ranking of potential opportunities (Butler et al. 2003), life-cycle costs for batteries, CAES, and flywheels (Schoenung and Hassenzahl, 2003), a general calculation of potential revenues in California and PJM without regard to technologies (Eyer et al., 2004), pumped hydroelectric storage using PJM market data (Perekhodtsev, 2004) and comparison of energy arbitrage revenues (from storing power purchased at off-peak times and selling it on-peak) in North American and European energy markets (Figueiredo et al., 2005).

In addition to the traditional applications described in section 1-3, the restructuring of the electricity industry has created additional opportunities for integration of EES into the electric grid and has provided a means to quantify the benefits of some of the traditional applications. This research has evaluated the economics of EES in wholesale electricity markets operated by New York ISO (NYISO) and the PJM Interconnection (PJM). The NYISO and PJM markets were chosen for this analysis because market data are readily available and an initial survey indicated that both energy arbitrage and regulation services might be profitable there. Figure 1-3 shows the average daily price curves for energy and ancillary service markets in NYISO based on 2001-07 average prices for each hour of the day. Below we have listed various markets operated by NYISO and PJM that allow EES to participate:

1-5-1. Energy Market (Day Ahead and Real Time): This market provides a mechanism for market participants to buy and sell energy. EES can buy energy at an off-peak price and sell during on-peak hours directly into the market or can be party to a bilateral contract.

1-5-2. Ancillary Services Markets: These markets support the transmission of real power and reactive power from resources to loads and are used to maintain reliable operation of the power grid.

- **Regulation and Frequency Support:** for the continuous balancing of resources with load, in accordance with NERC criteria. This service is accomplished by committing online generators whose output is raised or lowered, usually in response to an Automatic Generation Control (AGC) signal, as necessary to follow moment-by-moment changes in load.

- **Spinning (or Synchronized), Non-Spinning and Operating Reserves:** to provide backup generation in the case of a loss of major generating resources or transmission due to either to a power system contingency or equipment failure.

1-5-3. Installed Capacity Market: This market has been established to ensure that there is sufficient generation capacity to cover the capacity requirements. EES systems that meet the reliability criteria specified by the system operator can earn the capacity revenue in addition to energy arbitrage and ancillary service revenue.

1-5-4. Demand Response Programs: Both NYISO and PJM have developed emergency and economic demand response (DR) programs. Behind-the-meter (i.e. end use customer side of the utility meter) installations of EES technologies can be eligible to participate in demand response programs. Qualifying installations may also be eligible for capacity revenues under Special Case Resource (SCR) program in NYISO and Interruptible Load Resource (ILR) program in PJM.

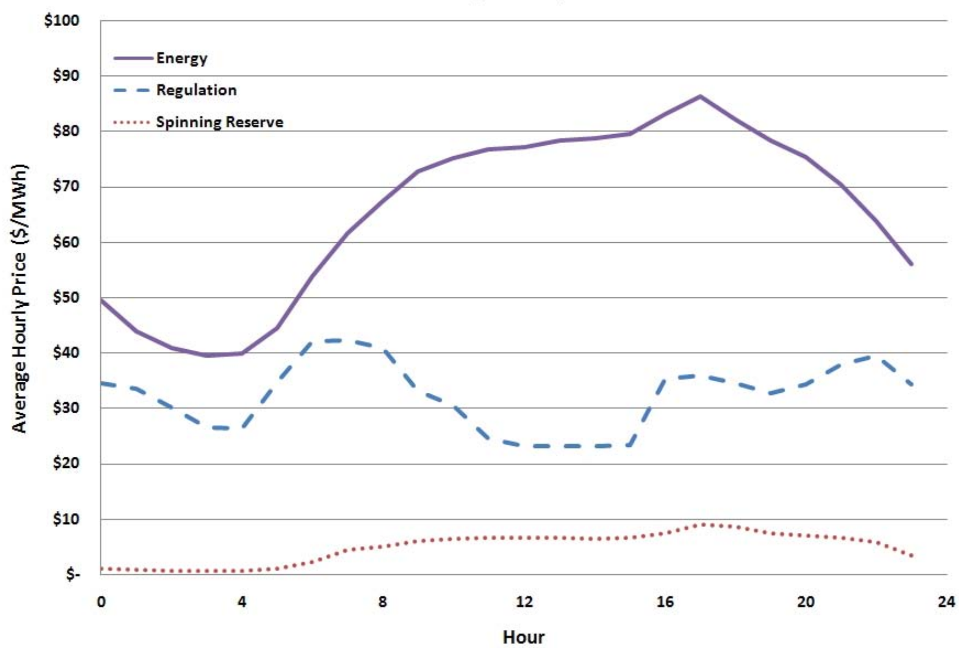


Figure 1-3. Average Daily Price Curves for Energy, Regulation, and Spinning Reserves in NYISO (2001-07) (Source: NYISO Market Data)

We note that VAR support is either a cost based or fixed price ancillary service in current markets, and is location dependent. No publically available data exist to evaluate VAR requirements that may be served by EES. Thus, performing market analysis for VAR support was not included in the agreed scope of this report.

Section 2 covers the economics of EES in the NYISO electricity market, and Section 3 covers the economics of EES in the PJM electricity market.

1-6. References for Section 1

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Appendix 1-A. Summary of EES Technologies (EPRI 2003, EPRI 2004, EPRI 2006, Schoenung 2003, Gyuk 2005, Price 2000)[3]

EES Technology	Advantages	Disadvantages	Major Applications	Customer	Potential Improvements
Lead Acid	❑ Mature technology - over a century old ❑ Familiar - the most widely used EES system on earth ❑ Inexpensive ($/kW) - $600 - $1600 ❑ Ready availability (45-50% of battery sales)	❑ Low specific energy (kWh/kg) and specific power (kW/kg) ❑ Short cycle life (100-1000) ❑ High maintenance requirements ❑ Environmental hazards (lead and sulfuric acid) ❑ Capacity falls with decreasing temperature below 77 degrees F	❑ Automobile ❑ UPS/Telecom/Substation reserve power	❑ Utilities (Generation, Transmission and Distribution) ❑ Residential, commercial, industrial customers ❑ Automobile end users	❑ Cycle Life ❑ Depth of Discharge (DOD) ❑ Performance at low ambient temperatures
Sodium Sulfur (NaS)	❑ High energy and power density ❑ Relatively high efficiency ❑ Long cycle life ❑ Relatively well-established	❑ Relatively expensive (still small volume manufacturing) ❑ High temperature produces unique safety issues	❑ Peak shaving for T&D upgrade deferral ❑ Small load leveling applications	❑ Utilities (Generation, Transmission and Distribution) ❑ Industrial customers	❑ Lower cost

[3] The authors acknowledge help and guidance from Mr. Haresh Kamath of EPRI and Mr. Rick Mancini of Customized Energy Solutions in developing this summary comparison.

EES Technology	Advantages	Disadvantages	Major Applications	Customer	Potential Improvements
Vanadium Redox Battery (VRB)	❑ Energy and power sizing is independent ❑ Scalable for large applications ❑ High energy and power density ❑ Easily upgradeable	❑ Relatively early-stage technology ❑ Relatively expensive ❑ Limited opportunities for standard sizes	❑ Peak shaving for &TD upgrade deferral ❑ Small load leveling applications ❑ Backup power applications	❑ Utilities (Generation, Transmission and Distribution) ❑ Industrial customers	❑ Lower costs ❑ Improved standardization ❑ Safety protocols for special locations (i.e., urban areas)
Zinc Bromine Battery (ZBB)	❑ Energy and power sizing are partially independent ❑ Scalable for large applications ❑ High energy and power density	❑ Relatively early-stage technology ❑ Potentially high maintenance costs ❑ Safety hazard: corrosive and toxic materials require special handling	❑ Peak shaving for T&D upgrade deferral ❑ Small load leveling applications ❑ Backup power applications	❑ Utilities (Generation, Transmission and Distribution) ❑ Industrial customers	❑ Lower costs ❑ Improved control methodology ❑ Improved safety protocols
Li-ion (Cobalt Oxide-based)	❑ High energy and power density ❑ Higher efficiency	❑ High cost - limited availability of cobalt ❑ Requires sophisticated battery management ❑ Safety issues require special handling	❑ Consumer electronics ❑ Automobile (hybrid electric vehicles and plug-in hybrid electric vehicles) ❑ Utility applications are possible	❑ Utilities (generation, transmission and distribution) ❑ Automobile and consumer electronics end users	❑ Lower costs ❑ Improved safety methodologies ❑ Improved thermal management systems ❑ Improved battery management systems

EES Technology	Advantages	Disadvantages	Major Applications	Customer	Potential Improvements
Li-ion (Phosphate-based)	❑ High energy and power density (though not as high as $LiCoO_2$-based) ❑ Higher efficiency ❑ Lower cost than $LiCoO_2$-based technologies	❑ Relatively early-stage technology ❑ Requires sophisticated battery management ❑ Safety issues (though safer than $LiCoO_2$-based technologies)	❑ Consumer electronics ❑ Automobile (hybrid electric vehicles and plug-in hybrid electric vehicles) ❑ Utility applications are possible	❑ Utilities (generation, transmission and distribution) ❑ Automobile and consumer electronics end users	❑ Lower costs ❑ Improved safety methodologies ❑ Improved cycle life ❑ Improved thermal management systems ❑ Improved battery management systems
Ni-Cd	❑ Mature technology ❑ Relatively rugged ❑ Higher energy density and ❑ Better cycle life than lead-acid batteries	❑ More expensive than lead-acid ❑ Limited long-term potential for cost reductions due to material costs ❑ Toxic components (cadmium)	❑ Utility/Telecom backup ❑ Consumer electronics	❑ Utilities (generation, transmission and distribution) ❑ Consumers	❑ Lower costs ❑ Improved recycling capability
NiMH	❑ Relatively mature technology ❑ Relatively rugged ❑ Higher energy density and ❑ Better cycle life than lead-acid batteries ❑ Less toxic components Ni-Cd	❑ More expensive than lead-acid ❑ Limited long-term potential for cost reductions due to material costs	❑ Utility/Telecom backup ❑ Consumer electronics	❑ Utilities (generation, transmission and distribution) ❑ Consumers	❑ Lower costs ❑ Improved recycling capability

EES Technology	Advantages	Disadvantages	Major Applications	Customer	Potential Improvements
Ultra-capacitors (Electric Double-Layer Capacitors)	❑ High power density ❑ High cycle life ❑ Quick recharge	❑ Low energy density ❑ Expensive ❑ Sloped voltage curve requires power electronics	❑ Power quality ❑ Emergency bridging power ❑ Fluctuation smoothing	❑ Industrial customers ❑ Utilities (distribution utilities with local renewable generation with potential for fluctuations)	❑ Lower costs ❑ Higher energy densities
SMES	❑ High power	❑ Low energy density ❑ Large parasitic losses ❑ Expensive	❑ Power quality ❑ Emergency bridging power	❑ Utilities (IOUs, integrated utilities)	❑ Lower costs ❑ Higher energy densities ❑ Faster recharge
Flywheels	❑ High power density ❑ High cycle life ❑ Quick recharge ❑ Independent power and energy sizing	❑ Low energy density ❑ Large standby losses ❑ Potentially dangerous failure modes`	❑ Frequency regulation ❑ Power quality ❑ Emergency bridging power ❑ Fluctuation smoothing	❑ Industrial customers ❑ Utilities (IOUs, integrated utilities)	❑ Lower costs ❑ Higher energy densities
CAES	❑ Huge energy and power capacity	❑ Geographically limited ❑ Requires fuel input ❑ Long construction time ❑ Large scale only	❑ Energy arbitrage ❑ Frequency regulation ❑ Ancillary services	❑ Utilities (IOUs, integrated utilities)	❑ Adiabatic capability (requires thermal storage)

EES Technology	Advantages	Disadvantages	Major Applications	Customer	Potential Improvements
Pumped Hydro	❑ Huge energy and power capacity	❑ Geographically limited ❑ Expensive to site and build ❑ Long construction time ❑ Large scale only	❑ Energy arbitrage ❑ Frequency regulation ❑ Ancillary services	❑ Utilities (IOUs, integrated utilities)	❑ Turbine efficiency

2: Economics of Electric Energy Storage in New York

2-1. Introduction: NYISO Markets and EES

The New York Independent System Operator (NYISO) administers the wholesale energy markets in New York State. NYISO's electricity markets include installed capacity, energy, and ancillary services. Approximately 45% of New York electricity is transacted in the NYISO day-ahead market, 5% in the NYISO real-time market, and 50% through bilateral contracts (NYISO 2005a).

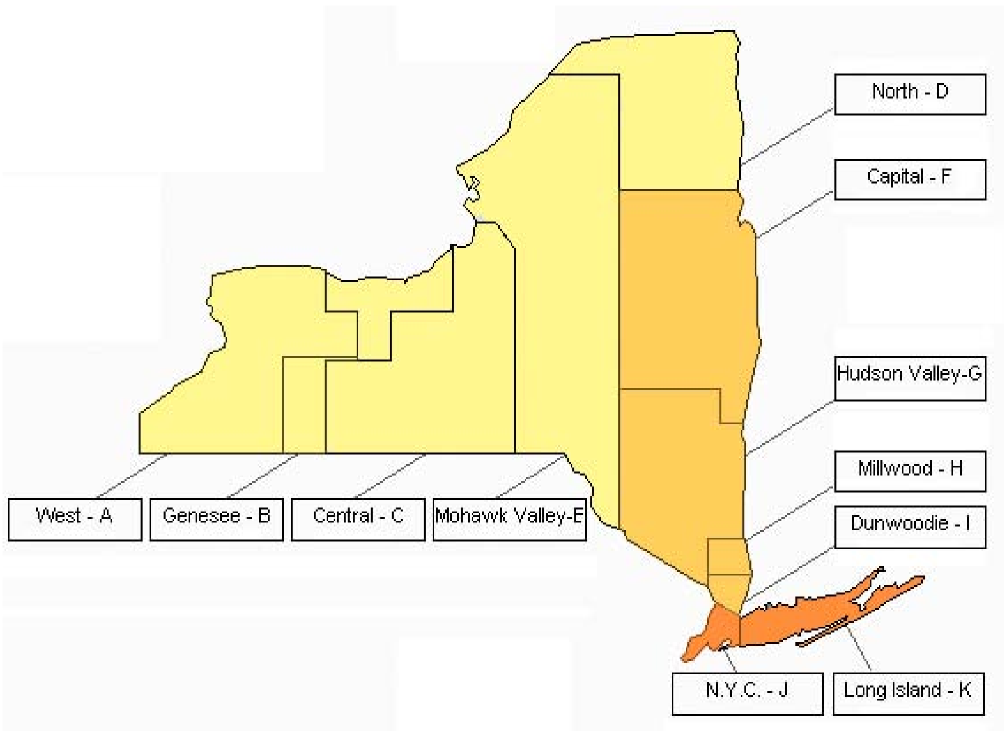

Figure 2-1. The Eleven NYISO Market Zones Grouped Into Three Regions

Based on NYISO LBMP Map © NYISO.

We have aggregated the eleven zones defined by NYISO (Figure 2-1) into three (Table 2-1). These regions are distinct in terms of geography and in energy price distribution. There is a clear similarity in the peak and off-peak prices in the zones in each region. This pattern is observed in all three periods used for this analysis: the complete year, the summer capabilities period, and the winter capabilities period.

Table 2-1. NYISO Zones and Regions Used In This Analysis

Region	Zones
NY West	• West (A) • Genesee (B) • Central (C) • North (D) • Mohawk (MH) Valley (E)
NY East	• Capital (F) • Hudson Valley (G) • Millwood (H) • Dunwoodie (I)
New York City	• NYC (J) • Long Island (K)

Table 2-2. NYISO Zone Location-Based Marginal Price Distribution for 2001-2007

		Peak ($/MWh)			Off Peak ($/MWh)		
Region	**Zone**	**All Year**	**Summer**	**Winter**	**All Year**	**Summer**	**Winter**
New York City	**Long Island**	$82.94	$85.65	$80.19	$59.69	$59.67	$59.70
	NYC	$79.73	$82.51	$76.91	$53.35	$53.34	$53.35
NY East	**Capital**	$65.32	$65.07	$65.57	$47.46	$45.71	$49.23
	Dunwoodie	$69.62	$72.15	$67.05	$48.40	$47.34	$49.48
	Hudson Valley	$68.06	$70.01	$66.09	$47.82	$46.59	$49.08
	Millwood	$68.98	$71.51	$66.40	$47.98	$46.88	$49.09
NY West	**Central**	$58.25	$58.75	$57.74	$42.18	$41.15	$43.23
	Genesee	$56.89	$57.48	$56.29	$40.62	$39.58	$41.68
	MH Valley	$60.09	$60.60	$59.58	$43.74	$42.76	$44.75
	North	$57.72	$57.79	$57.64	$42.78	$41.71	$43.86
	West	$54.32	$55.35	$53.27	$38.77	$37.95	$39.60

Table 2-2 lists the distribution of the mean location-based marginal price (LBMP) for different zones and seasons for the 2001-2007 period. Correlation analysis of the zonal LBMP prices was also performed to test the validity of grouping the eleven zones into our three regions. All zones in the NY West region have a correlation coefficient higher than 0.98, and all zones in the NY East region have a correlation coefficient higher than 0.96. New York City and Long Island have a lower correlation coefficient of 0.82, but these zones showed a much greater degree of correlation with each other than with the other zones. Appendix 2-A-1 includes additional tables of mean values of LBMP data for each year from 2001-2007 that justified the grouping of these zones into three regions.

2-2. The Analytic Framework: Market Scenario Analysis

NYISO has recognized in its market design special resources that have limited electric energy output capability for short time periods and/or require a recharge period (NYISO 2005a). These energy-limited resources (ELRs), that are generally peaking plants or demand-side resources must demonstrate the ability to deliver energy for a minimum of four consecutive hours each day. Thus, NaS batteries can be utilized as ELRs (for energy arbitrage), whereas flywheels cannot. The latter are particularly well-suited for providing regulation service due to the very high cycle life.

The net revenues for each market can be calculated as follows: Energy arbitrage net revenue is the difference between revenue received from energy sale (discharge) during 'N' peak hours and the charging cost for off-peak energy, that includes a factor ($1/\eta$) for additional energy required due to losses, where η is the round-trip efficiency. Let T_{DS} denote the starting hour of discharge, T_{CS} the starting hour of the charging period, $P_{Energy}(t)$ the LBMP price of energy for the corresponding hour, and $Q_{Energy}(t)$ the amount of energy delivered during the hour. Then

$$(2\text{-}1)\ \sum R_{Energy}(t) = \sum_{t=T_{DS}}^{T_{DS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)] - \frac{1}{\eta} \sum_{T_{CS}}^{T_{CS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)]$$

Regulation and frequency response service revenues are calculated based on the market-clearing price for the regulation service. EES are paid for both charging and discharging when responding to appropriate regulation signals from the ISO. The EES' cost to provide regulation depends on the round-trip efficiency, as the EES must pay for the energy consumed during the regulation cycle.

$$(2\text{-}2) \sum R_{regulation}(t) = \sum_{t=T_{DS}}^{T_{DS+N(regulation)}} P_{regulation}(t) * |Q_{regulation}(t)| - (1-\eta) \sum_{T_{CS}}^{T_{CS+N(regulation)}} [P_{Energy}(t) * |Q_{regulation}(t)|]$$

Appendix 2-A-2 lists the binding constraints for these equations. A global optimization for operation of EES providing a combination of energy and ancillary services would require data such as distribution of hours for operating reserve pickups (the actual delivery of energy by units selected for providing operating reserves) and detailed technical data to analyze the effect of changing operational parameters on capital cost; these data are not available. In the next section we examine the economics of EES under different scenarios by comparing the net revenues that can be generated from a 1 MW EES for different applications.

2-3. Energy Arbitrage Revenues

We have analyzed the energy arbitrage potential of energy-limited resources for energy delivery times of 10 hours, 4 hours, and 2 hours. These periods of energy arbitrage were selected based on two criteria: First, EES technologies considered for long-duration energy arbitrage have efficiencies between 65% and 85% (the ratio of input power to output power is ~ 1.2 - 1.4). Assuming that these units are charged and discharged at the same rate, this results in 20-40% additional charging time, limiting the maximum duration for energy sale to 10 hours. Second, NYISO allows EES participating under the energy-limited resources program to receive capacity credits if they can provide energy for 4 successive hours (NYISO 2005a). Thus for an application with energy arbitrage as the only service, 4 hours of energy discharge capability was considered as the minimum duration necessary for market participation.

NYISO market energy data from 2001-2004 were used to determine the statistical net revenue potential for three different operating conditions (2-hour, 4-hour, and 10-hour). For determining the net revenues, the maximum potential revenue period and the minimum potential cost period for each day in the three regions were determined. Appendix 2-A-3 provides details of the analysis.

The maximum electricity price period has a relatively wide distribution and shows a seasonal shift in the maximum revenue period. The maximum revenue period for 4-hour energy arbitrage is from 12 a.m. to 4 p.m. in the summer period, and shifts to 3 p.m. to 7 p.m. in the winter period. This information was used in calculating the anticipated revenues by using the LBMP for corresponding hours. Under the base scenario it was assumed that a market participant will bid in the EES resources based on the historical data for the seasonal forecast for peak hours. With the use of better forecasting tools utilizing weather data, load forecasts, and historical prices, market participants may be able to increase revenue by capturing peak and least-cost periods on a weekly or even daily basis.

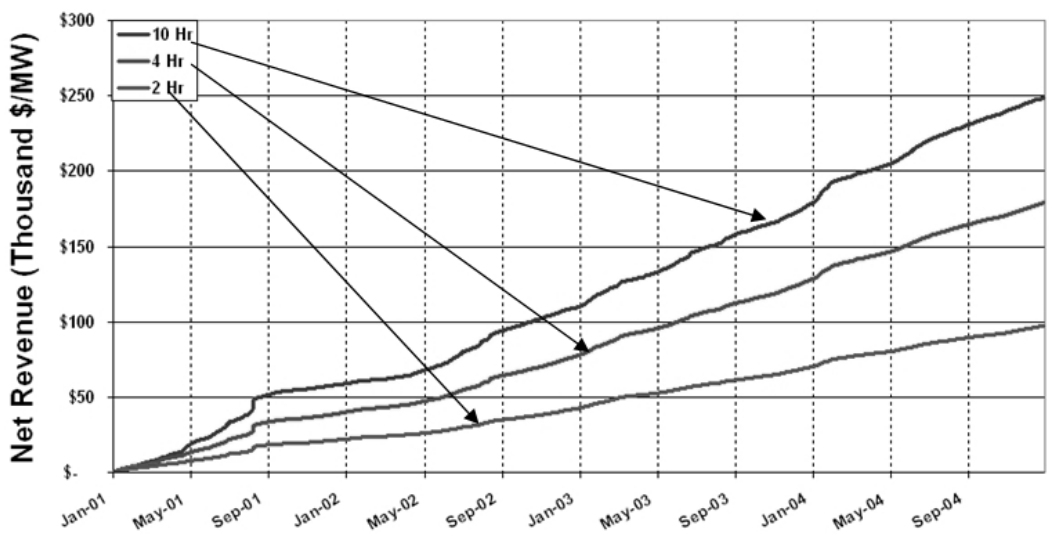

Figure 2-2. Cumulative Net Revenue (2001-2004) from Energy Arbitrage in New York City

Figure 2-2 shows the potential cumulative net revenues (i.e. the difference between the energy revenues and the charging cost) for different durations of energy arbitrage in the New York City region during the 2001-2004 period. The total net revenue was determined by using a 1-MW-sized energy storage unit for 10-hour, 4-hour, and 2-hour energy arbitrage. The base case efficiency was initially assumed to be 83% (a ratio of input energy to output energy of 1.2). For this efficiency, 10-hour energy arbitrage would have generated approximately $250,000 of revenue during the 2001-2004 period in New York City. The energy arbitrage revenues for 4-hour and 2-hour sales would have been approximately $170,000 and $100,000 respectively.

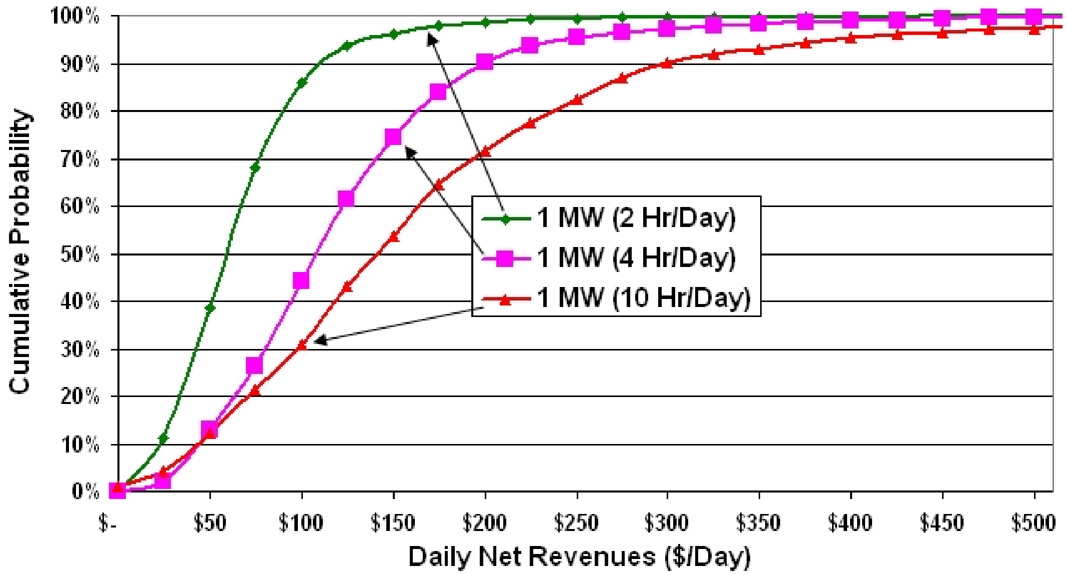

Figure 2-3. Cumulative Probability Distribution of Daily Net Revenues for Energy Arbitrage in New York City

Figure 2-3 shows the cumulative probability distribution of daily net revenues that would have been received during 2001-2004 by an EES unit for energy arbitrage for 2-hour, 4-hour, and 10-hour periods. Although the marginal net revenue from operating the unit for shorter durations (2 or 4 hours) is significantly higher than from operating the unit for 10 hours, the operator receives more total daily revenue when the units are run for a longer duration. There is a 50% probability that the EES will receive over $50/MW-day in net revenues for 2- hour energy arbitrage. This net revenue increases to over $105/MW-day for 4-hour and $140/MW-day for 10-hour operations.

If the power rating of EES and the rate of discharge are not limiting factors, then an EES with a 10 MWh energy capacity could theoretically be operated at higher power levels for shorter periods of time. A unit might be used for energy arbitrage delivering 1 MW for 10 hours, 2.5 MW for 4 hours, or 5 MW for 2 hours. In practice, operations would be limited by the unit's power rating and the power conversion system. A more detailed analysis involving capital cost estimates is required to determine if it is more economical to deploy EES units that are able to provide 2 to 4 hours of required energy at higher power levels.

2-4. Effect of Round-Trip Efficiency

The net revenue from energy arbitrage is highly sensitive to EES efficiency because inefficient systems are forced to buy some peak power. Figure 2-4a shows the expected net revenues from energy arbitrage for 2001-2004 in the New York City region from a 1-MW EES, as a function of efficiency. In New York City, an EES with round-trip efficiency of less than 73% would earn more net revenues for 4-hour energy arbitrage than for 10-hour.energy arbitrage. An EES unit with efficiency of less than 67% would earn more net revenues from 2-hour energy arbitrage than from 10-hour energy arbitrage. Lower round-trip efficiency means that the EES must be charged for longer duration, increasing charging costs, and reducing the price differential between peak and off-peak operation. Due to the different energy prices in the three regions, the switchover points between these operating modes occur at slightly different efficiencies for the various geographic regions. Figure 2-4b shows a similar graph for the NY West region.

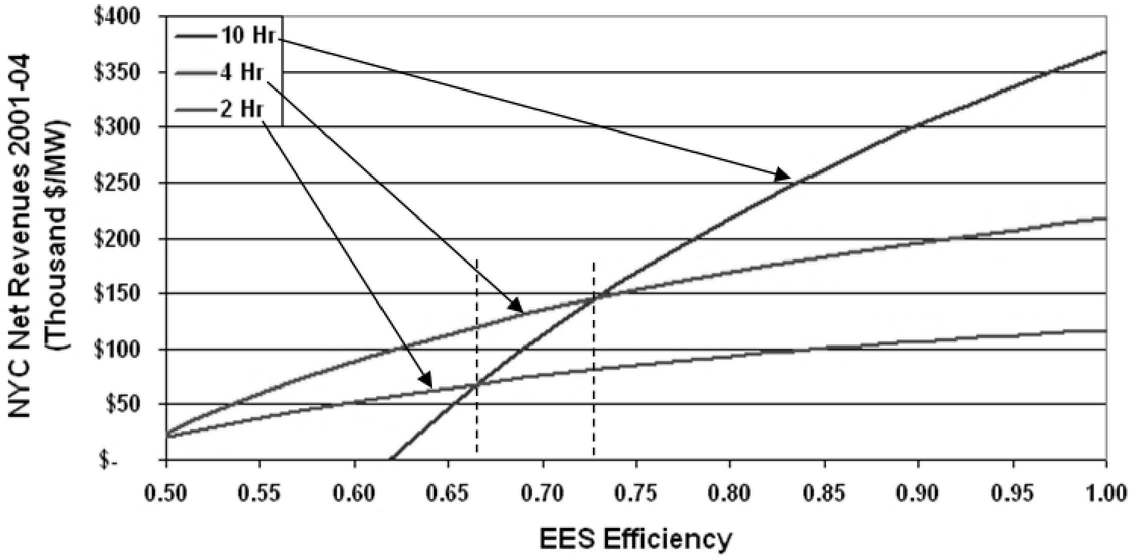

Figure 2-4a. Cumulative Net Revenues as a Function of EES Efficiency in the New York City Region

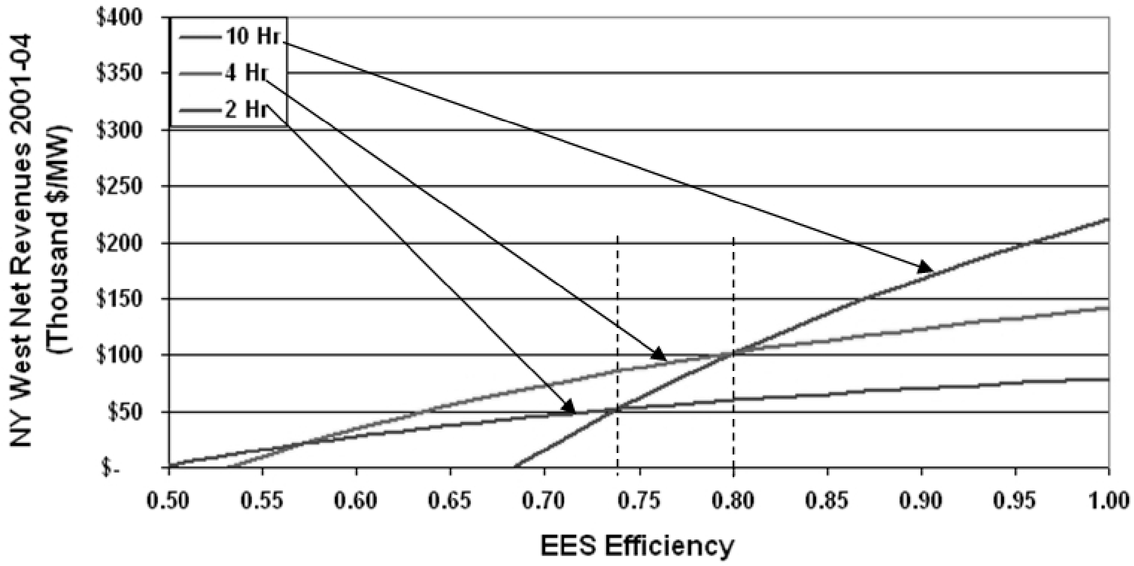

Figure 2-4b. Cumulative Net Revenues as a Function of EES Efficiency in the New York West Region

The net revenue from energy arbitrage is highly sensitive to the round-trip efficiency of the EES. Round-trip efficiency can be used to determine the energy rating of the EES and the maximum duration of energy arbitrage that can operated economically.

2-5. Installed Capacity Market (ICAP)

ICAP revenues are designed to encourage new additions of generation capacity in areas with small supply reserve margins. Any EES capable of providing four hours or more of capacity can generate ICAP revenues in addition to the revenues received from energy or ancillary markets. Table 2-3 shows the summary results for the ICAP monthly market auctions for 2004-2005. There are also locational requirements for New York City (zone J) and Long Island (zone K) that require Load Serving Entities (LSE) serving these areas to procure a certain percentage (80% and 99% respectively) of the regional peak load from resources within the individual zones (NYISO, 2005a). Due to this locational requirement, the ICAP revenues for the NYC region are significantly higher than for the rest of the state and contribute significantly towards making EES operations economical in this region.

Table 2-3. ICAP Revenues 2004-2007 (NYISO, 2008b)

	Minimum Market clearing price ($/kW-Month)	**Average Market clearing price ($/kW-Month)**	**Maximum Market Clearing Price ($/kW-Month)**
New York City	$5.60	$9.07	$12.54
Rest of State	$1.58	$2.29	$3.00

2-6. Regulation Revenue

EES can be used for providing various required ancillary services: 1) regulation services required to track moment-to-moment fluctuations in load and supply and 2) reserve services for meeting intra- and inter-hour changes in the supply and load curves (NYISO 2005b).

Regulation and frequency response services assist in maintaining the system frequency at 60 Hz and allow compliance with reliability criteria set by NERC, the New York State Reliability Council (NYSRC), and the Northeast Power Coordinating Council (NPCC).

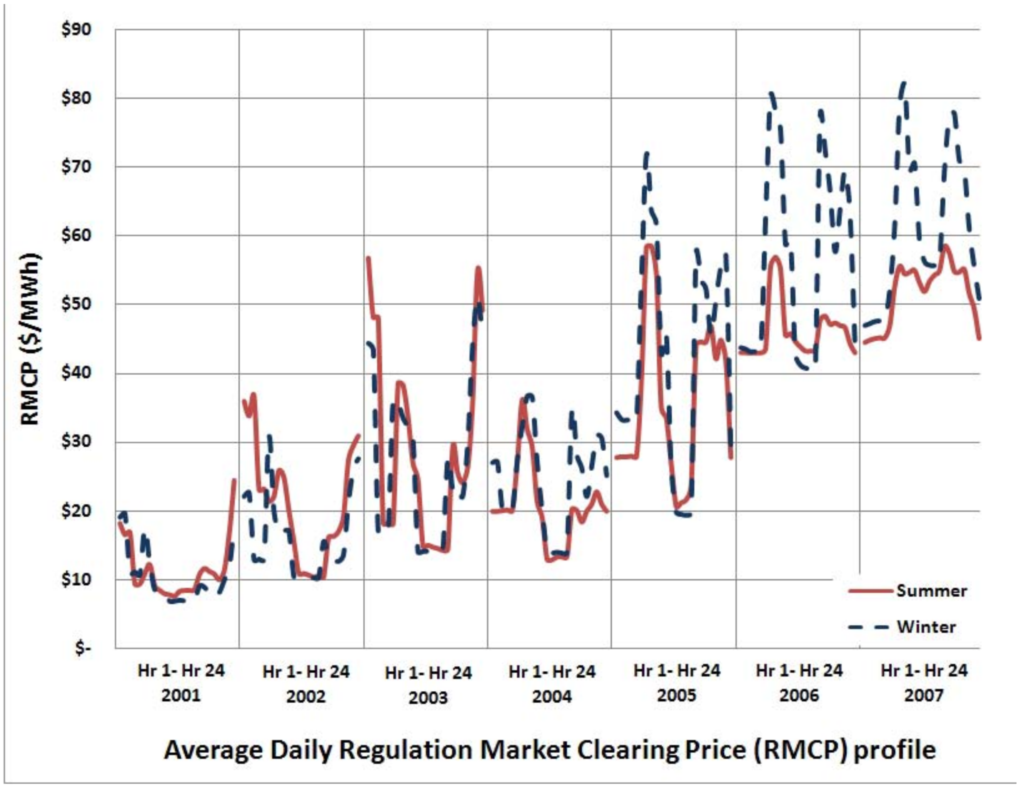

Figure 2-5. Average Daily Regulation Market Clearing Price (RMCP) Profiles for NYISO During 2001-2007

Resources providing regulation service are directed to move from each real-time dispatch base point (usually every 5 minutes) in 6-second intervals at their stated ramp rate (Hirst 2001). Figure 2-5 shows the average daily regulation market-clearing price (RMCP) profiles for the years 2001-2007. These curves show the average RMCP price for each hour of the day during the year for the summer capabilities period and the winter capabilities period. During both the summer and winter capabilities periods the regulation prices are higher than average during the morning pickup and evening drop-off hours, when the system load changes rapidly. In recent years the value of regulation during these peak periods has been significantly higher during the winter months than during the summer months due to higher fuel prices.

Resources can participate in the regulation market if they have automatic generation control capability within the New York control area. Some EES technologies, particularly flywheels, can be used to offer regulation services. Flywheels cannot be utilized for energy applications due to their short duration (15-minute) energy storage capacity. For pumped hydro facilities, Perekhodtsev (2004) has shown that frequency regulation can offer one of the highest value markets for storage. In NYISO, our work shows that regulation offers the maximum revenue potential among all the ancillary services, followed by spinning, non-spinning, and 30 minute operating reserves (Walawalkar et al. 2005). Figure 2-6 shows the annual average price for regulation and spinning reserves for NYISO from 2001 to 2007.

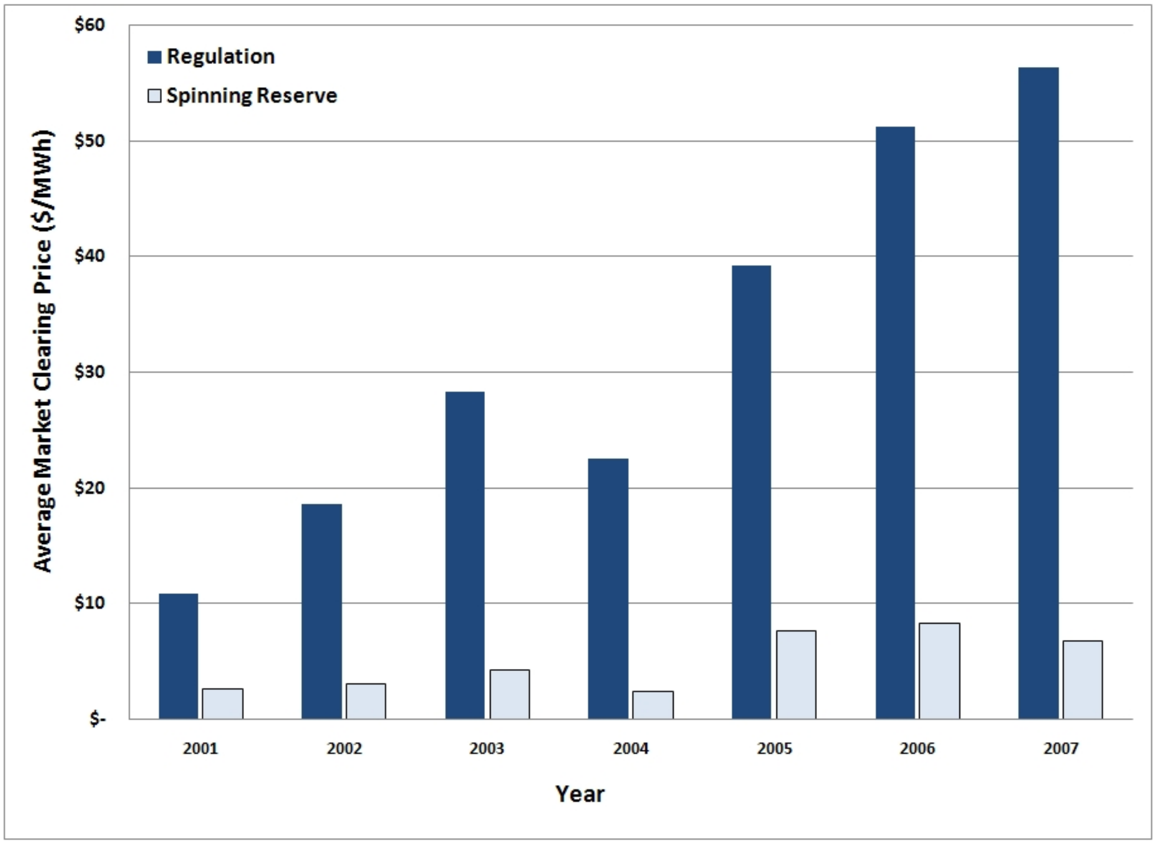

Figure 2-6. Annual Average Regulation and 10-Minute Spinning Reserve Prices for NYISO (2001-2007)

2-7. EES Economics

Table 2-4 summarizes the expected net revenue for energy arbitrage (with round-trip efficiency of 75%) and regulation in all three regions. The maximum-case scenario represents the data from the year with maximum net revenues (2006), whereas the minimum-case scenario represents the year with minimum net revenues (2003). The estimates for average net revenues were calculated using the average revenue and cost figures from 2001-2007 market data. (NYISO, 2008a)

Table 2-4. Summary of Potential Annual Net Revenues for Various Applications by Region

Application	**Expected Net Revenue (Thousand $/MW-year)**		
	New York City ***Min - Avg - Max***	***NY East*** ***Min - Avg - Max***	***NY West*** ***Min - Avg - Max***
Energy Arbitrage 10 Hours*	$91 - $150 - $192	$26 - $47 - $66	$22 - $35 - $44
Energy Arbitrage 4 Hours* + Synchronous Reserve 15 Hours	$112 - $189 - $254	$57 - $89 - $125	$46 - $75 - $102
Regulation 24 Hours	$59 - $201 - $370	$67 - $212 - $389	$75 - $222 - $401

*** Includes capacity revenue.**

New York City has the highest revenue potential for energy arbitrage of the three regions in New York State. In NY East and NY West, regulation services have the maximum revenue potential and the lowest uncertainty (regulation prices have less variance than energy prices). However, there is some regulatory uncertainty in utilizing flywheels for regulation services. Flywheels have much smaller regulation capacity per installation and rely on the changing sign of the regulation control signal, so that the unit can be continuously charged and discharged (i.e., an average zero net energy regulation signal). Currently flywheel manufacturers and NYISO officials are attempting to develop ways to determine an appropriate evaluation criterion for calculating the performance of flywheels for regulation services. (The original evaluation criteria were devised for large central generators providing regulation services by the use of automated generation controls.)

2-8. Additional Benefits

Since most current installations of EES are based on the valuation of the benefits offered by EES for either power reliability or system upgrade cost deferral, we have approximately quantified these benefits based on a review of the literature. The benefits accrue to different market participants. For example, the deferral of system upgrade costs is important to utilities or LSEs, whereas commercial and industrial customers value the power quality and reliability benefit (Butler et al. 2003; EPRI 2003; Eyer et al. 2004).

- **Power quality and reliability:** The benefits of power quality and reliability depend on the monetary cost associated with power system events that can cause customer interruptions. For commercial and industrial customers, one estimate for annual outage hours is 2.5 hours per year and a value-of-service of $20/kWh (Eyer et al. 2004). Thus the annual reliability benefit is $50/kW-year or $50,000/MW-year. Similarly, power quality benefits can be calculated based on a survey of existing research and known data related to power quality. Earlier studies indicate a benefit of \$5/kW-event and 20 events per year, or \$100,000/MW-year (Eyer et al., 2004). Combined power quality and reliability benefits can thus be estimated as \$150,000/MW-year. These are societal benefits and are difficult for an EES operator to capture except when an EES is utilized at a customer facility to provide power quality and reliability. In certain cases in regulated markets, the regulator may allow recovery of EES costs related to power quality and reliability.

- **System upgrade cost deferral:** A properly located EES can allow utilities to defer transmission and distribution upgrade costs. Such suitable locations can be characterized by infrequent maximum load days with peak load occurring during only a few hours in a day. Also locations with slow load growth can utilize an EES for a few years to defer T&D upgrade. These benefits could range from \$150,000 - \$1,000,000/MW-year (EPRI 2003; Eyer et al. 2004).

2-9. Net Present Value Analysis

Based on the range of annual net revenue estimates and the EES cost data, the net present value (NPV) was calculated for various EES technologies in different regions to evaluate the economics of these technologies. The discount rate used was 10%, and the project life considered was 10 years. Table 2-5 provides summary of all financial parameters used in the NPV simulations.

Table 2-5. Summary of Financial Parameters

	NaS Battery	**Flywheel**
Capital Cost (\$/kw)	\$1,500-\$2,000-\$3,000	\$750-\$1,500-\$2,000
O&M Cost (\$/kw-yr)	\$30	\$25
Disposal cost (\$/kw)	\$15	-
Round-trip Efficiency	75%	85%
Discount factor	10%	10%

We performed Monte Carlo simulations that used NYISO market data to study the effect of capital cost, round-trip efficiency, and location on the distribution of NPV. This simulation was performed for 1,000 iterations using a triangular distribution for the net revenue for 4-hour energy arbitrage combined with 15 hours of synchronized reserve for a NaS battery in all three regions. Similar simulations were also performed for flywheels using a triangular distribution of net revenue from regulation. The minimum, maximum, and average values for net revenue were selected for each region based on the data presented in Table 2-4. The minimum revenue was for year 2002, maximum revenue was for year 2005 and 2001-2007 average revenue was used for the average value of the triangular distribution. To be conservative, we used \$150,000/MW-year as the average value for the system upgrade deferral or power quality and reliability benefit of NaS, and $100,000/MW-year as the average value for the power quality benefits of flywheels to augment the revenues that can be realized by a typical market participant in New York.

A sensitivity analysis performed on the various financial parameters for calculating NPV of NaS batteries for energy arbitrage indicates that the T&D benefits, capital costs, and annual revenues are the top 3 factors influencing the NPV of project. Appendix 2-A-4 shows the details of the sensitivity analysis.

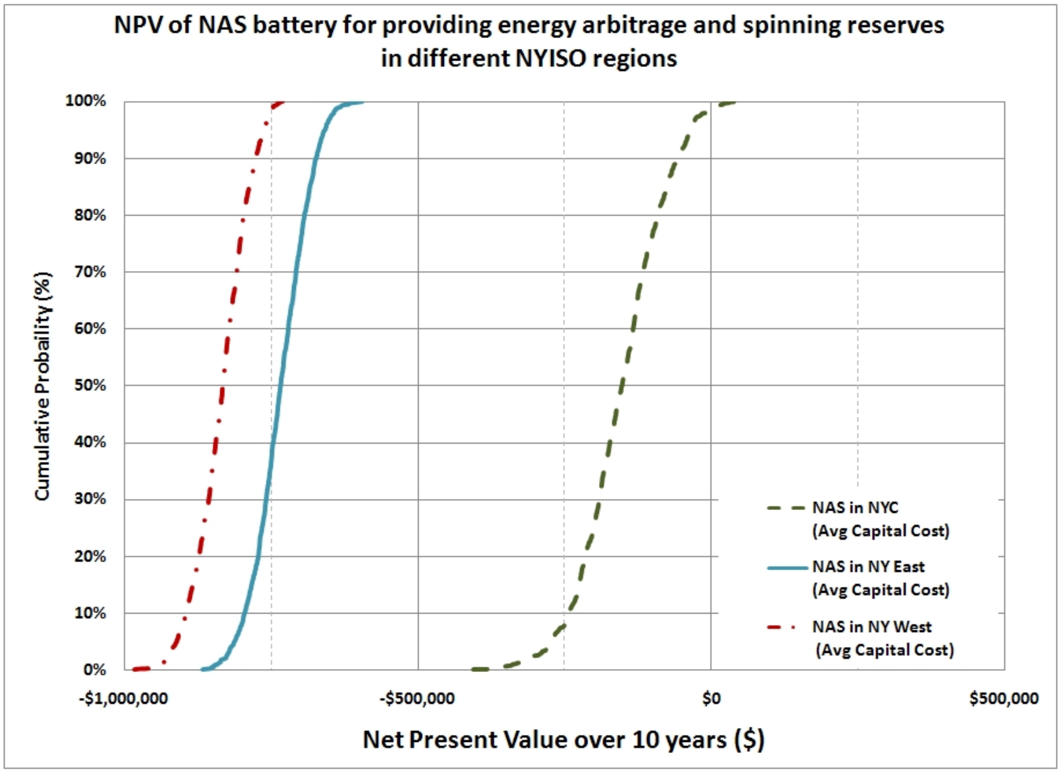

Figure 2-7a. Effect of The Location of an Installation on the Cumulative Probability Distribution of NPV for an NaS Installation for 4-Hour Energy Arbitrage and 15 Hours of Spinning Reserves Across NYISO Regions With Average Capital Cost

Figure 2-7a shows the NPV distribution for a NaS installation in all three regions using the average cost estimates for capital and operation and maintenance (O&M) costs for a NaS installation. From Figure 2-7a, it can be seen that for the expected capital cost of $2000 / KW, the NPV is negative in all three regions, including New York City, where the operating revenues are significantly higher than other regions due to higher capacity credits and energy prices. Figure 2-7a shows that the mean NPV for a NaS installation in New York City is approximately -$150,000, whereas similar units in NY East and NY West have mean NPVs of -$730,000 and -$830,000, respectively. The major factor contributing to the uncertainty of the NPV of the project is the variation in the energy revenues and charging costs from the actual market data.

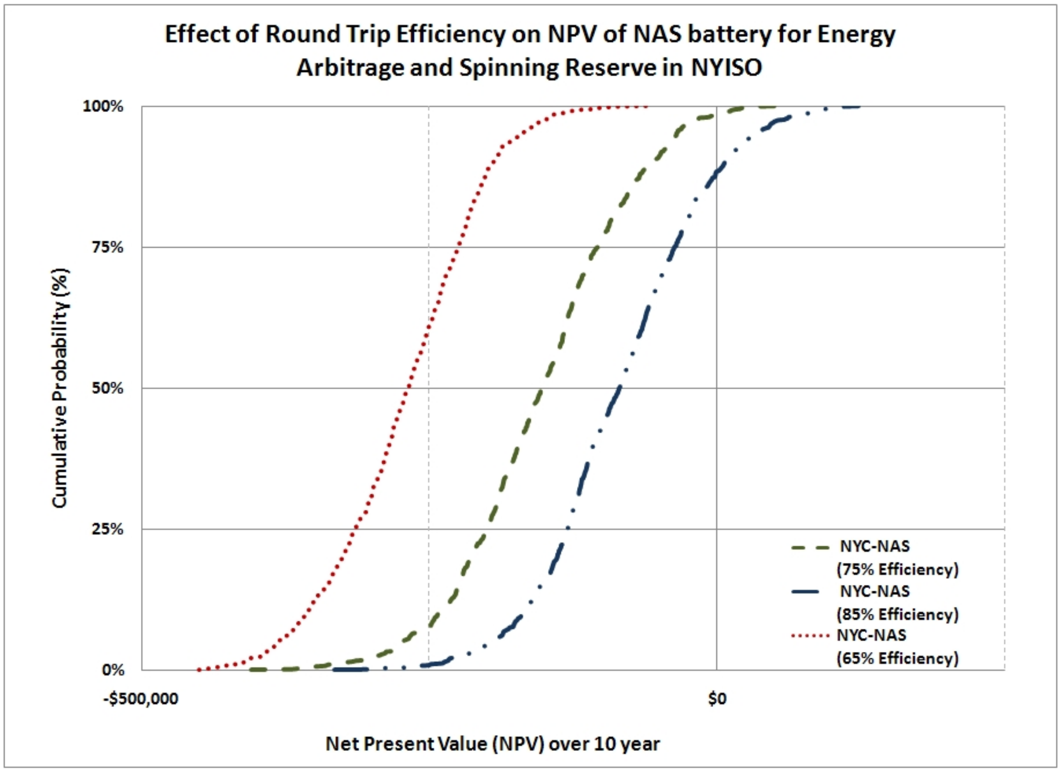

Figure 2-7b. Effect of Round-Trip Efficiency on the Cumulative Probability Distribution of NPV for a NaS Installation for 4-Hour Energy Arbitrage and 15 Hours of Spinning Reserves in NYC With Average Capital Cost.

Since the net revenues from energy arbitrage are significantly affected by the round-trip efficiency of the EES, we performed additional simulations to evaluate the effect of change in round-trip efficiency on the NPV of a NaS installation for energy arbitrage and spinning reserve in NYC. The results of the simulation are shown in figure 2-7b. Although with higher round-trip efficiency of 85% there is a 12% probability that the NaS installation in New York City would have a positive NPV, the mean NPV was approximately -$85,000. The mean NPV dropped to -$270,000 for a round-trip efficiency of 65%.

We also performed simulations to understand the effect of the capital cost on the NPV of a NaS battery. Figure 2-7c shows the results of Monte Carlo simulations performed for three scenarios of capital cost estimates using an average round-trip efficiency of 75%. We used $1,500/KW as a best-case scenario and $3,000/KW for a scenario with a higher than expected capital cost estimate. With the best-case scenario, the mean NPV for NaS installation is approximately $350,000, whereas in the worst-case scenario the mean NPV is -$1,150,000.

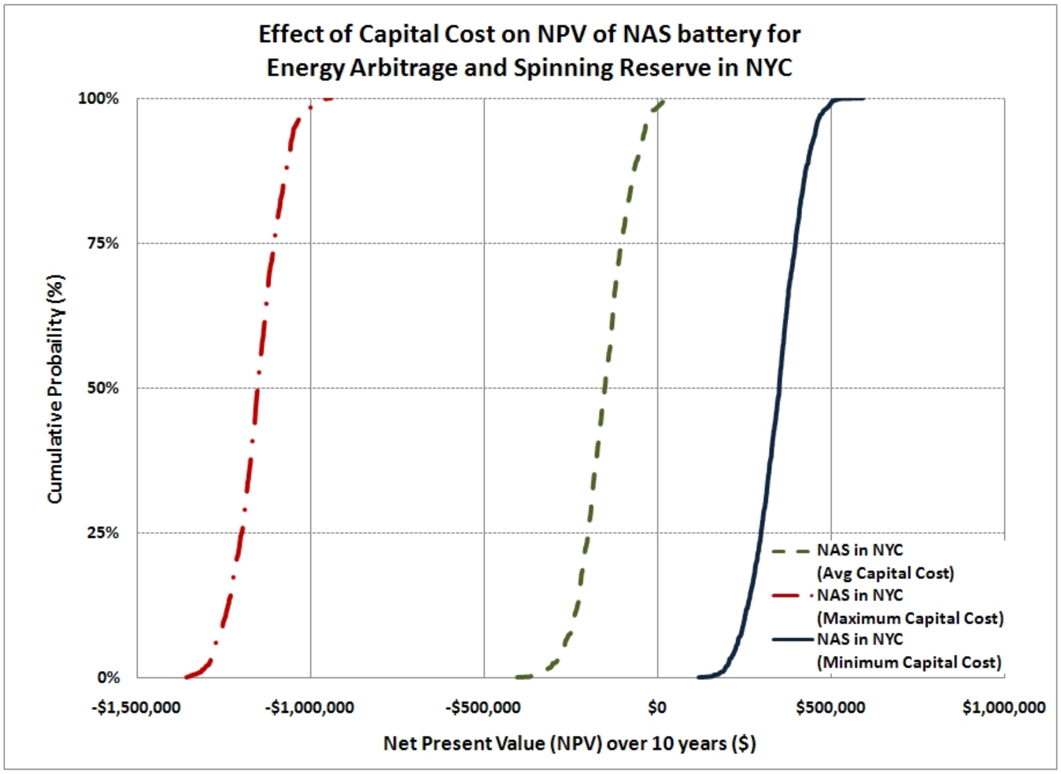

Figure 2-7c. Effect of Capital Cost on the Cumulative Probability Distribution of NPV of NaS For 4-Hour Energy Arbitrage and 15 Hours of Spinning Reserves in NYC

Next, we compared the NPV of flywheels for providing 24-hour regulation in NY West (with the highest net revenues for regulation) to the NPV of a NaS in NYC with average cost and average round-trip efficiency. We used the capital cost estimate of $1,500/KW for flywheels with a round-trip efficiency of 85% as a base-case scenario. The results shown in Figure 2-8a suggest that there is a less than 1% probability of a negative NPV when flywheels are used for providing regulation in the NY West region. The mean NPV of using flywheels with a round-trip efficiency of 85% for regulation in NY West is $390,000.

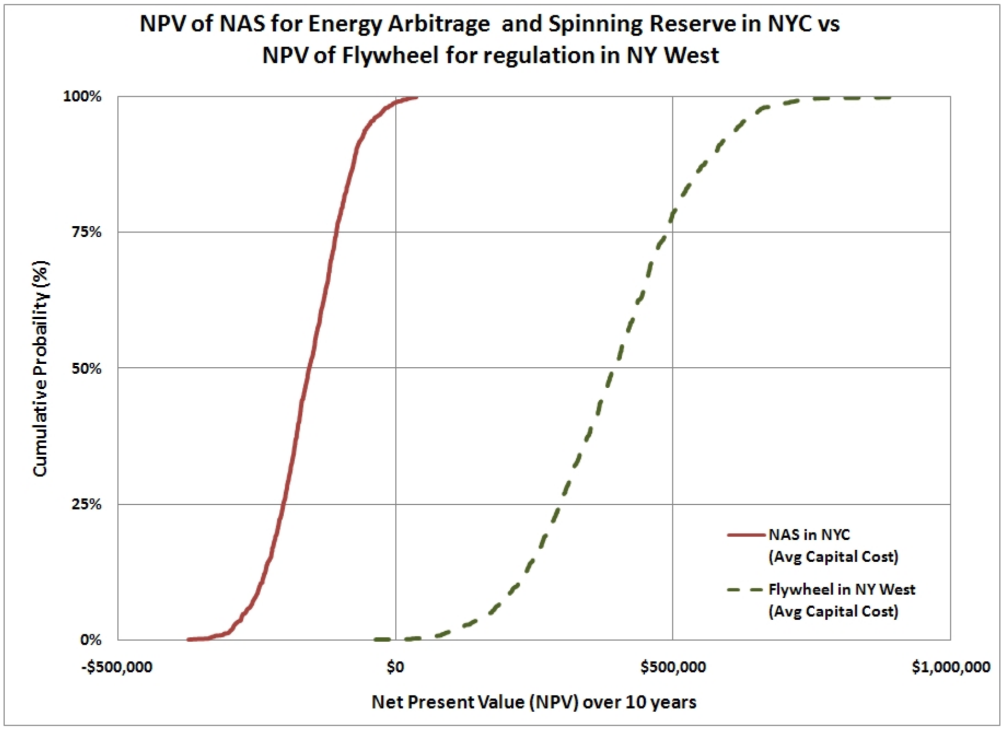

Figure 2-8a. Comparison of the Distribution of the NPV for Flywheels Used for 24-Hour Regulation in NY West and a NaS Battery Used for 4-Hour Energy Arbitrage and Spinning Reserve in New York City

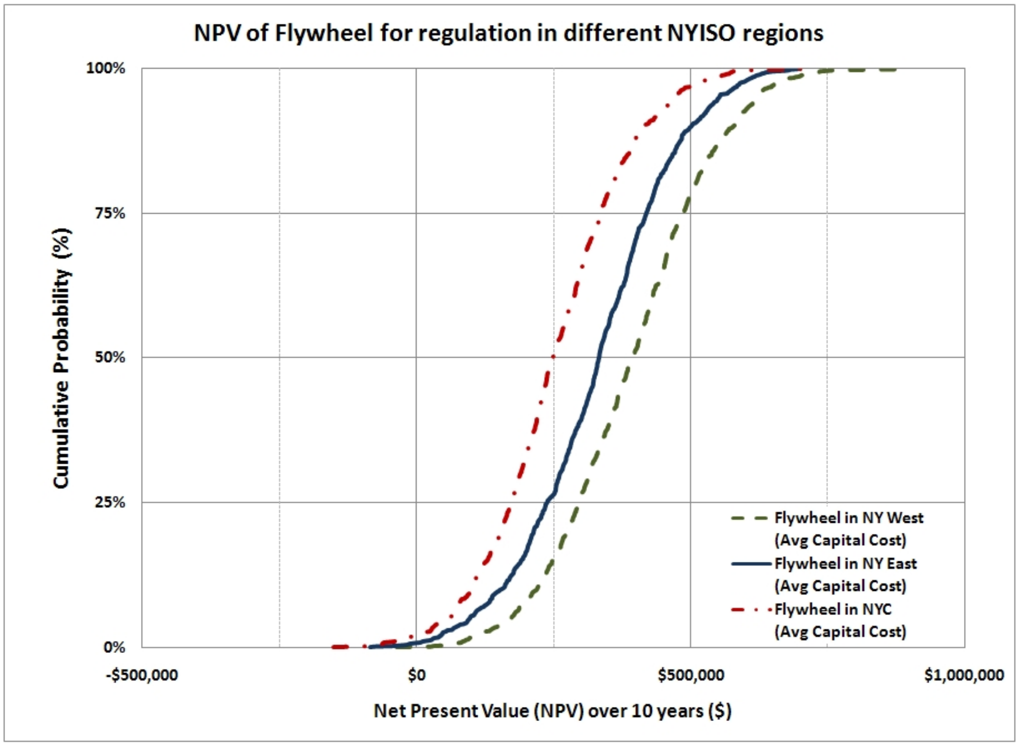

Figure 2-8b. Effect of Location on the Cumulative Probability Distribution of the NPV of Flywheels for Regulation in NYISO

Figure 2-8b shows the results of the Monte Carlo simulations to analyze the effect of location on the NPV of flywheels for providing regulation in NY. Since the regulation market-clearing price (RMCP) is the same across all NYISO regions, the difference in the NPV for providing regulation reflects energy costs to cover round-trip losses due to the differences in energy prices in these regions. Due to these higher energy costs, the mean NPV of flywheels for providing regulation drops to $330,000 and $250,000 respectively, in the NY East and NYC region.

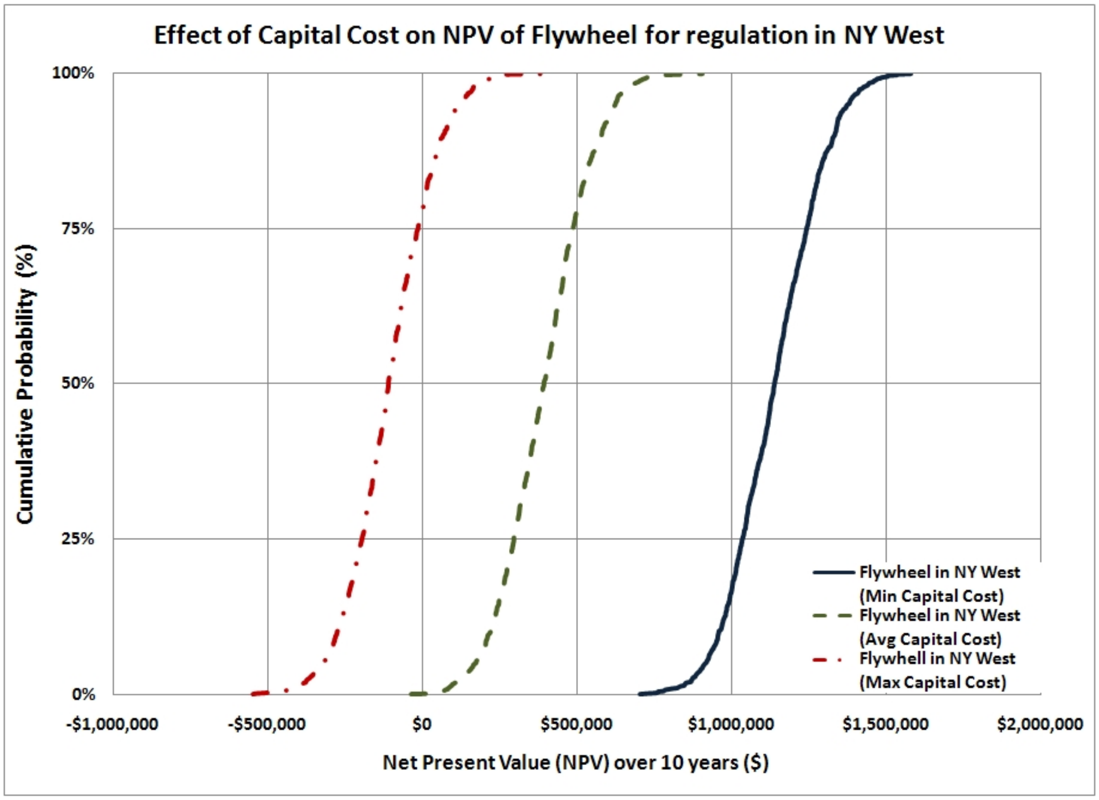

Figure 2-8c. Effect of Capital Cost on the Cumulative Probability Distribution of NPV of Flywheels for Providing Regulation in NY West

Similar to NaS batteries, capital cost has a significant effect on the NPV of using flywheels for regulation in NY. Figure 2-8c indicates that for a scenario with the capital cost of flywheels at $2,000 /KW instead of $1,500/KW in the base-case scenario, the mean NPV from providing 24 hours of regulation dropped to -$110,000. On the other hand, in the best-case scenario of $750/KW as the capital cost, the mean NPV increased to $1,140,000 from the base-case scenario of $390,000.

2-10. Conclusion

EES technologies capable of discharging at higher power and energy densities than conventional lead-acid batteries can offer benefits to various market participants in competitive electricity markets. There are technical as well as market barriers for the wide-scale integration of electric energy storage for wholesale market applications.

- Market rules should be changed to resolve uncertainty related to the energy limited nature of EES in regulation markets. NYISO is currently considering a rule change that would mandate a response rate of greater than 90% from regulation units, which could result in disqualification of energy limited EES such as flywheels (which may have as much as 40% idle time based on the nature of the regulation signal). If adopted, this rule would inhibit the adoption of flywheels. The market rules for regulation should recognize the limited energy availability as well as faster response time provided by energy storage technologies. This would require that the regulation signal sent to these devices be customized to ensure that units such as flywheels are not sitting idle due to their energy limited nature. The California ISO is currently evaluating such an option to introduce a separate category of regulation services through fast response energy storage technologies.

- Our analysis indicates that the case for EES to participate in regulation market could be further enhanced if the opportunity costs paid to traditional generators are captured as part of the regulation market clearing price (RMCP) in PJM. PJM is considering changes to the RMCP payment that may include EES.
- The current market rules related to synchronized reserves permit that the service can be provided by generators synchronized to the grid operating on no load. Thus although EES can meet the technical requirements of synchronized reserves, the market rules should ensure that EES is eligible to receive synchronous reserve payments, by making reserve payments technology independent. PJM has already modified market rules to allow demand response participation in the ancillary service markets and NYISO is currently working on similar modifications; EES should receive similar consideration.

At present, most energy storage technologies have higher capital costs than peaking power alternatives such as gas turbines (flywheels are similar in capital cost to a combined-cycle natural gas turbine, and NaS batteries have two to four times the capital cost of an NGCC unit). While capital costs are falling somewhat due to technology improvements, significant manufacturing economies of scale have not yet been realized (EPRI 2003; 2004).

Based on market data from 2001-2007, we find that flywheels in the NY West region have a high probability of positive NPV for regulation. Significant opportunities exist in the NY East and NYC regions for regulation. We find that the market-based revenue streams are not sufficient to justify investment in NaS batteries for energy arbitrage and spinning reserves. There still may be opportunities for NaS in locations where the system upgrade deferral benefits are significantly higher than our conservative estimates used in this analysis.

EES units that require an average zero net energy regulation signal are sometimes denied participation in regulation markets. The New York State Research and Development Authority (NYSERDA) and the California Energy Commission (CEC) have initiated efforts to evaluate the performance of flywheels for providing regulation services in recent years. The results of these studies may support the wide deployment of such devices. Current market rules also do not permit most EES technologies to participate in 10-minute synchronous spinning reserve markets, that can offer roughly 15% of the revenue available from regulation (Walawalkar et al. 2005).

A recent analysis (Butler et al., 2003) argued that EES systems with low round-trip efficiency and low equipment cost would be viable for energy arbitrage. This research also indicates that achieving lower costs is critical for improving the economics of NaS batteries for energy arbitrage. At the same time, reducing capital costs by sacrificing efficiency can have a significantly adverse effect on the economics of the project, particularly for energy arbitrage. Thus while designing and developing EES systems for electricity market participation, it is crucial to maintain or increase efficiency while reducing the capital cost.

There are several factors that may improve the economics of energy arbitrage in the future. First, increased fuel prices for oil and natural gas can result in higher on-peak prices. At the same time NYISO is expecting more than 3000 MW of wind to be integrated in the NYISO system by 2012. As the maximum wind output may be available during the low load hours at night or early mornings, this could put downward pressure on off-peak prices in NY. These two factors can result in higher net revenues for energy arbitrage that could somewhat improve the economics of NaS batteries in NYISO in the future.

On the other hand, potential implementation of a price on carbon dioxide emissions may result in higher increases in off peak prices than peak prices due to due to the higher carbon content of coal typically used as fuel for base load plants (Newcomer et. al. 2008). This can result in lower net revenues from energy arbitrage, thus weakening the economic case for NaS.

The increasing penetration of intermittent renewable generators in the electricity grid could enhance the economics of future EES projects. NYISO is anticipating over 3000 MW of wind being added to the grid by 2012. Although this represents approximately 10% of the peak load for NYISO, wind could contribute to 20-30% of the off peak energy requirements, due to lower system loads at night. This may result in downward pressure on off peak electricity prices, thus improving the economics of energy arbitrage. In addition, the variability of wind could result in an increased requirement for ancillary services, increasing revenues for EES for ancillary services including regulation and operating reserves.

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Appendix 2-A-1. Regional Distribution of Energy Prices

Appendix 2-A summarizes the statistical analysis of the zonal LBMP prices for the 11 NYISO zones for the complete year, the summer capabilities period, and the winter capabilities period, based on 2001-2007 data.

For NYISO's operations, the peak period is defined as the hours between 7 AM and 11 PM inclusive, prevailing Eastern Time, Monday through Friday, except for North American Electric Reliability Council (NERC)-defined holidays. The off-peak period is defined as the hours between 11 PM and 7 AM, prevailing Eastern Time, Monday through Friday; all day Saturday and Sunday; and NERC-defined holidays. NYISO has defined the summer capability period as May 1 through October 31 and the winter capability period as November 1 through April 30.

Table 2-A1. Regional Distribution of Peak LBMP Prices ($/MWh) for 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	Long Island	$59.78	$57.48	$73.53	$72.23	$113.39	$100.68	$103.67
	NYC	$56.39	$55.43	$77.42	$76.41	$112.53	$86.07	$93.94
NY East	Capital	$49.45	$46.23	$60.23	$60.41	$89.98	$70.43	$80.57
	Dunwoodie	$52.65	$47.69	$61.82	$62.30	$95.83	$78.86	$88.28
	Hudson Valley	$51.97	$46.70	$61.26	$60.96	$92.85	$76.52	$86.27
	Millwood	$51.79	$46.80	$61.19	$61.48	$95.03	$78.50	$88.16
NY West	Central	$43.74	$38.85	$55.08	$55.72	$81.36	$63.57	$69.44
	Genesee	$42.25	$38.00	$54.33	$55.21	$79.88	$62.01	$66.58
	MH Valley	$44.91	$39.69	$56.79	$57.43	$83.85	$65.90	$72.13
	North	$43.29	$38.31	$55.10	$55.54	$80.63	$62.56	$68.63
	West	$41.48	$36.37	$51.47	$52.22	$76.07	$58.67	$63.97

Table 2-A2. Regional Distribution of Peak LBMP Prices ($/MWh) for the Summer Capabilities Period 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	**Long Island**	$59.29	$66.51	$69.32	$72.28	$127.85	$105.91	$98.54
	NYC	$58.59	$63.69	$72.88	$73.80	$126.82	$89.71	$92.31
NY East	**Capital**	$50.60	$51.93	$55.44	$58.54	$97.24	$67.82	$74.08
	Dunwoodie	$55.35	$52.86	$59.00	$61.23	$107.06	$82.26	$87.40
	Hudson Valley	$54.52	$51.82	$57.85	$59.72	$102.89	$78.84	$84.50
	Millwood	$54.38	$52.02	$58.23	$60.48	$106.50	$81.89	$87.17
NY West	**Central**	$45.32	$41.80	$51.02	$53.68	$88.97	$62.98	$67.62
	Genesee	$43.95	$40.84	$50.40	$52.83	$87.46	$62.11	$64.95
	MH Valley	$46.60	$42.47	$52.52	$55.14	$91.49	$65.64	$70.50
	North	$44.92	$40.69	$50.76	$52.58	$87.41	$61.62	$66.72
	West	$43.53	$39.97	$47.57	$50.24	$84.21	$59.14	$62.90

Table 2-A3. Regional Distribution of Peak LBMP Prices ($/MWh) for Winter Capabilities Period 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	**Long Island**	$60.29	$48.24	$77.84	$72.17	$98.82	$95.27	$108.93
	NYC	$54.13	$46.97	$82.07	$78.96	$98.12	$82.31	$95.60
NY East	**Capital**	$48.27	$40.38	$65.15	$62.23	$82.66	$73.12	$87.22
	Dunwoodie	$49.89	$42.39	$64.72	$63.34	$84.51	$75.35	$89.18
	Hudson Valley	$49.37	$41.46	$64.75	$62.17	$82.73	$74.13	$88.09
	Millwood	$49.14	$41.45	$64.22	$62.45	$83.47	$74.99	$89.17
NY West	**Central**	$42.12	$35.83	$59.23	$57.71	$73.69	$64.18	$71.31
	Genesee	$40.50	$35.09	$58.35	$57.53	$72.25	$61.91	$68.25
	MH Valley	$43.18	$36.84	$61.17	$59.67	$76.15	$66.17	$73.80
	North	$41.63	$35.87	$59.55	$58.42	$73.80	$63.52	$70.59
	West	$39.38	$32.69	$55.47	$54.14	$67.88	$58.18	$65.06

Table 2-A4. Regional Distribution of Off-Peak LBMP Prices ($/MWh) 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	Long Island	$38.51	$39.42	$53.09	$54.89	$86.13	$73.50	$72.21
	NYC	$35.40	$37.92	$51.82	$51.33	$76.60	$57.72	$62.62
NY East	Capital	$32.71	$32.23	$43.87	$44.97	$66.62	$52.22	$59.55
	Dunwoodie	$33.09	$32.41	$44.18	$45.68	$68.90	$53.85	$60.66
	Hudson Valley	$33.03	$32.36	$44.04	$44.98	$67.06	$53.21	$60.05
	Millwood	$32.60	$32.00	$43.64	$45.14	$68.21	$53.62	$60.60
NY West	Central	$29.56	$28.20	$39.84	$41.02	$60.06	$46.43	$50.15
	Genesee	$28.48	$27.50	$39.17	$40.50	$58.46	$44.99	$45.25
	MH Valley	$30.57	$29.07	$41.31	$42.53	$62.42	$48.12	$52.17
	North	$30.11	$28.51	$40.60	$41.69	$61.20	$46.72	$50.59
	West	$28.07	$26.48	$37.06	$38.19	$55.26	$42.83	$43.48

Table 2-A5. Regional Distribution of Off-Peak LBMP Prices ($/MWh) for Summer Capabilities Period 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	Long Island	$36.54	$42.76	$50.51	$56.06	$94.01	$70.84	$66.81
	NYC	$34.32	$41.40	$49.96	$50.18	$82.57	$56.45	$58.36
NY East	Capital	$31.17	$33.01	$40.44	$42.93	$70.62	$48.44	$53.25
	Dunwoodie	$32.08	$33.13	$41.17	$43.96	$73.89	$51.01	$56.00
	Hudson Valley	$31.93	$32.95	$40.93	$43.14	$71.42	$50.32	$55.31
	Millwood	$31.46	$32.70	$40.56	$43.42	$73.26	$50.76	$55.87
NY West	Central	$28.68	$27.87	$36.86	$38.61	$63.65	$44.62	$47.63
	Genesee	$27.63	$27.15	$36.36	$37.88	$61.84	$43.65	$42.45
	MH Valley	$29.70	$28.61	$38.26	$40.04	$66.28	$46.42	$49.89
	North	$29.28	$27.83	$37.59	$38.84	$65.01	$44.90	$48.40
	West	$27.38	$26.59	$34.32	$35.56	$59.11	$41.87	$40.74

Table 2-A6. Regional Distribution of Off-Peak LBMP Prices ($/MWh) for Winter Capabilities Period 2001-2007

Region	Zone	2001	2002	2003	2004	2005	2006	2007
New York City	**Long Island**	$40.49	$36.05	$55.70	$53.67	$78.06	$76.18	$77.67
	NYC	$36.50	$34.40	$53.69	$52.54	$70.48	$58.99	$66.92
NY East	**Capital**	$34.27	$31.44	$47.34	$47.09	$62.51	$56.02	$65.92
	Dunwoodie	$34.11	$31.68	$47.23	$47.47	$63.78	$56.71	$65.36
	Hudson Valley	$34.14	$31.76	$47.19	$46.90	$62.58	$56.12	$64.84
	Millwood	$33.75	$31.30	$46.74	$46.93	$63.03	$56.49	$65.38
NY West	**Central**	$30.45	$28.54	$42.85	$43.53	$56.38	$48.25	$52.70
	Genesee	$29.33	$27.85	$42.02	$43.24	$54.99	$46.33	$48.08
	MH Valley	$31.45	$29.54	$44.41	$45.13	$58.46	$49.83	$54.48
	North	$30.95	$29.20	$43.65	$44.65	$57.29	$48.54	$52.80
	West	$28.76	$26.37	$39.84	$40.93	$51.32	$43.80	$46.25

Appendix 2-A-2. Binding Constraints

The binding constraints for the equations for calculating revenues from various energy markets can be expressed as

- $\mathrm{N_{Energy}} * \mathrm{Q_{Energy}} \le 0.8 * \mathrm{N_{Max}} * \mathrm{Q_{Max}}$
  i.e., the total energy delivered is less than or equal to 80% of the rated maximum energy capacity of the EES.
- $0.5 \le \eta \le 0.9$ i.e., the round-trip efficiencies of the EES devices considered are in the range of 0.5 to 0.9.
- $0 \le \mathrm{N_{Energy}} \le \mathrm{N_{Max}} \le \left(24 * \eta / (1+\eta)\right)$ or $0 \le \mathrm{N_{DSR}} \le \mathrm{N_{Max}} \le \left(24 * \eta / (1+\eta)\right)$
  The maximum duration for energy arbitrage or DSR participation is limited by the lower of the rated maximum discharge duration or $\left(24 * \eta / (1+\eta)\right)$, where η is the efficiency of EES. For example, the maximum duration for an EES with an efficiency of 1 would be 24/2 = 12 hours, i.e., 12 hours to charge and 12 hours to discharge.
- $0 \le N_{regulation} \le (24 - (\eta + 1/\eta) * N_{Energy})$
  The maximum duration for providing regulation is calculated by subtracting the number of hours required for energy arbitrage (both charge and discharge) from 24 hours. For flywheels, since regulation is the only service provided, it can be utilized for all 24 hours.
- $0 \le \left(N_{Spinning}\ Or\ N_{NonSpin}\ Or\ N_{30\min Operating}\right) \le N_{Max} \le \left(24 - (\eta + 1/\eta) * \left(N_{Energy}\right) - N_{regulation}\right)$
  Similarly, a market participant can utilize the remaining capacity of the EES for providing remaining ancillary services, depending on its technical capability and the market rules.

Appendix 2-A-3. Determining the Operating Hours for Energy Arbitrage

A statistical analysis of the energy price data from 2001-04 was performed to determine the net revenue potential for 3 different operating conditions (2 Hour, 4 Hour and 10 Hour). For determining the net revenues, the maximum potential revenue period and minimum potential cost period for each day in the 3 regions were analyzed.

Figure 2-A-1 shows the flowchart explaining the methodology used to determine the operating hours for energy arbitrage i.e. least cost charging hours and maximum revenue hours for discharging the EES during summer and winter capability period. Figures 2-A-2 and 2-A-3 show distribution of 4 hour maximum revenue period during winter and summer capability months during 2001-2004. Figures 2-A-4 and 2-A-5 show distribution of 4 hour minimum revenue period during winter and summer capability months during 2001-2004. Please note that the period is specified by the 1st hour of the starting period, i.e., for a 4 hour operation, Max Hour 16 indicates, the period from 4 PM - 8 PM had maximum revenue potential for a 4 hour energy arbitrage.

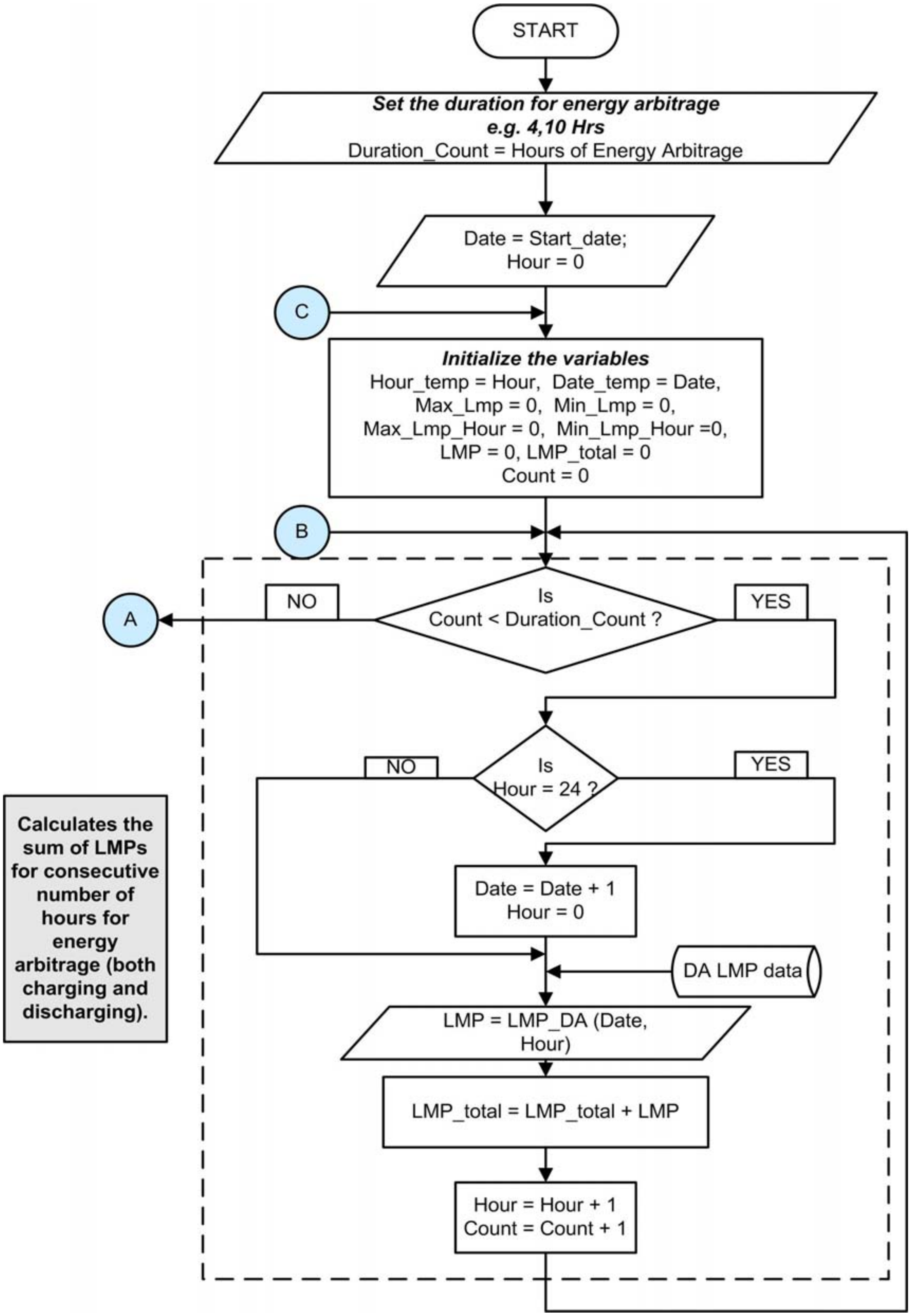


Figure 2-A1. Flowchart Explaining Methodology Used for Determining the Operating Hours for Energy Arbitrage **…continued on next page**

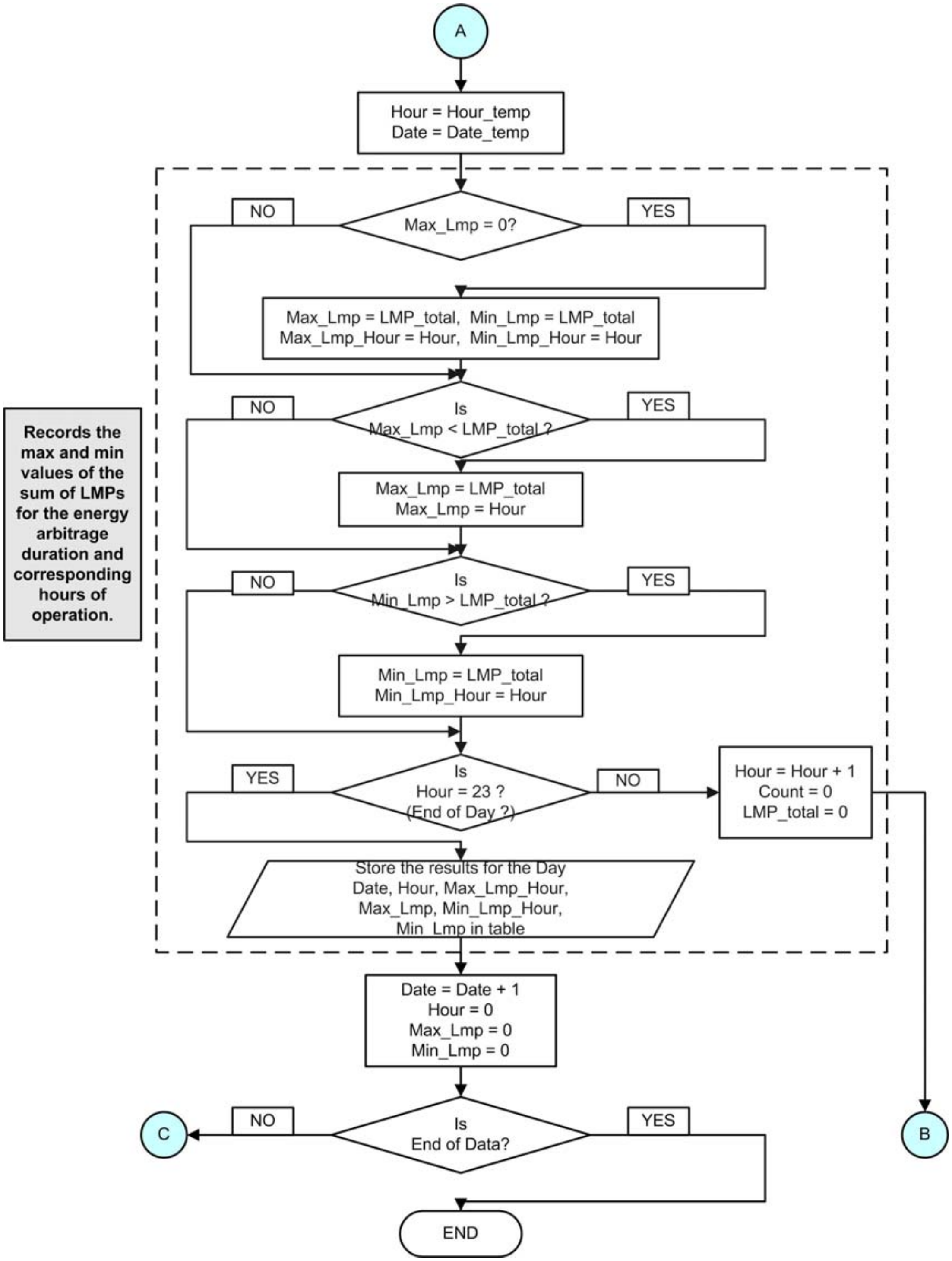


Figure 2-A1. (Continued)

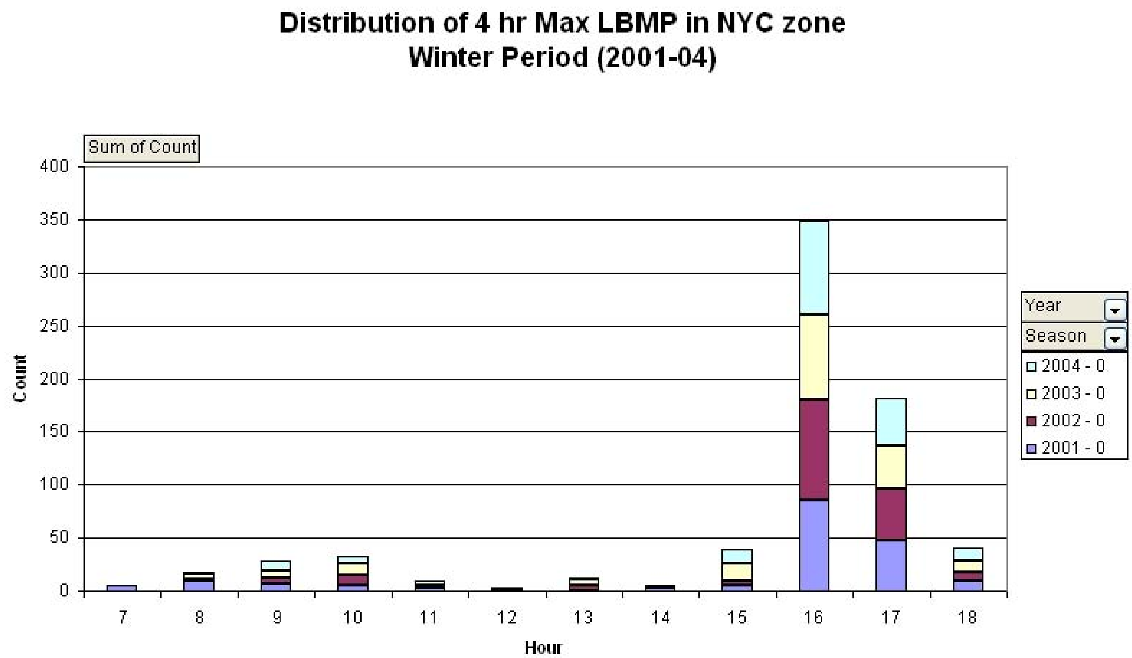


Figure 2-A2. Distribution of 4 Hour Maximum LBMP in NYC Zone 2001-04 – Winter Period

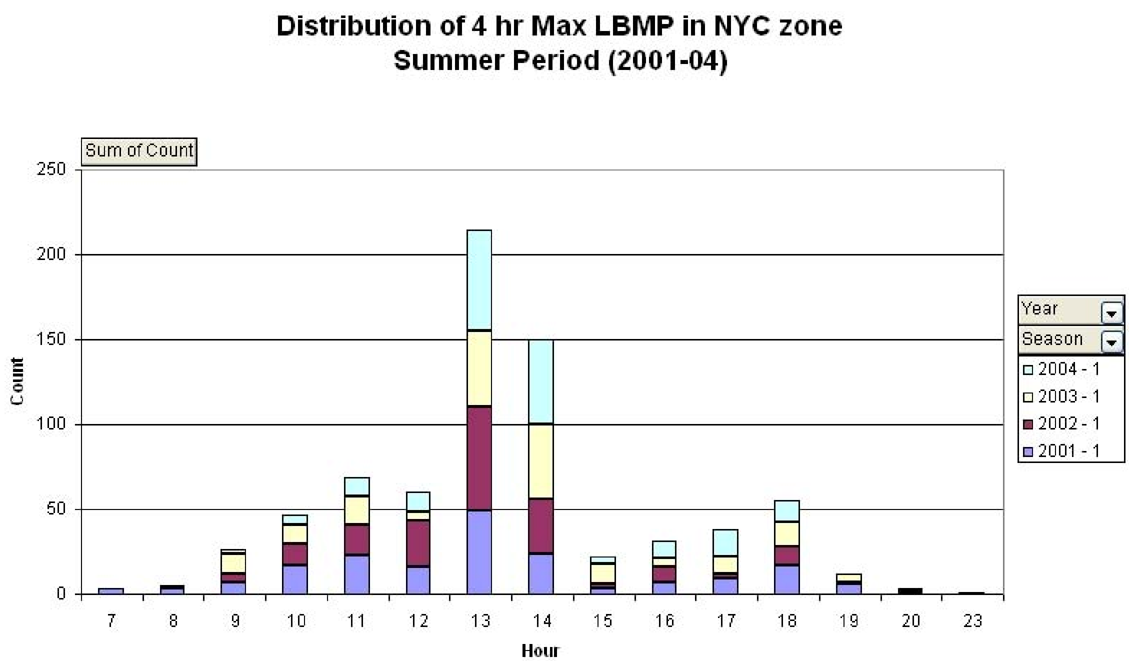


Figure 2-A3. Distribution of 4 Hour Maximum LBMP in NYC Zone 2001-04 – Summer Period

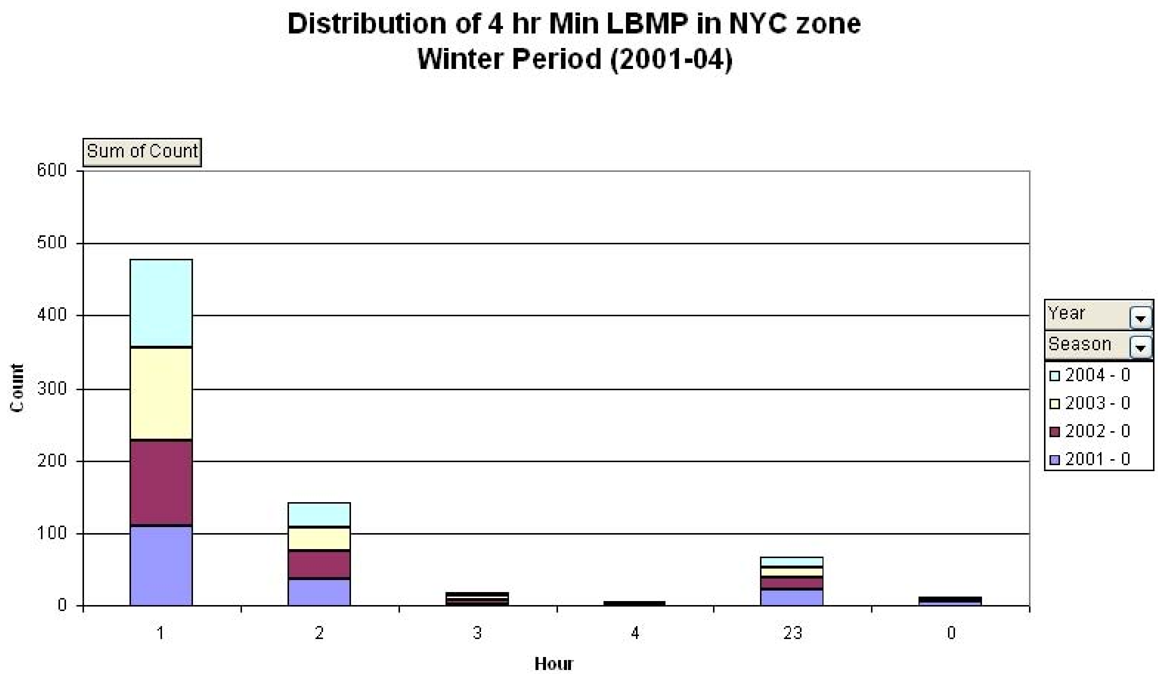


Figure 2-A4. Distribution of 4 Hour Minimum LBMP in NYC Zone Winter 2001-04.

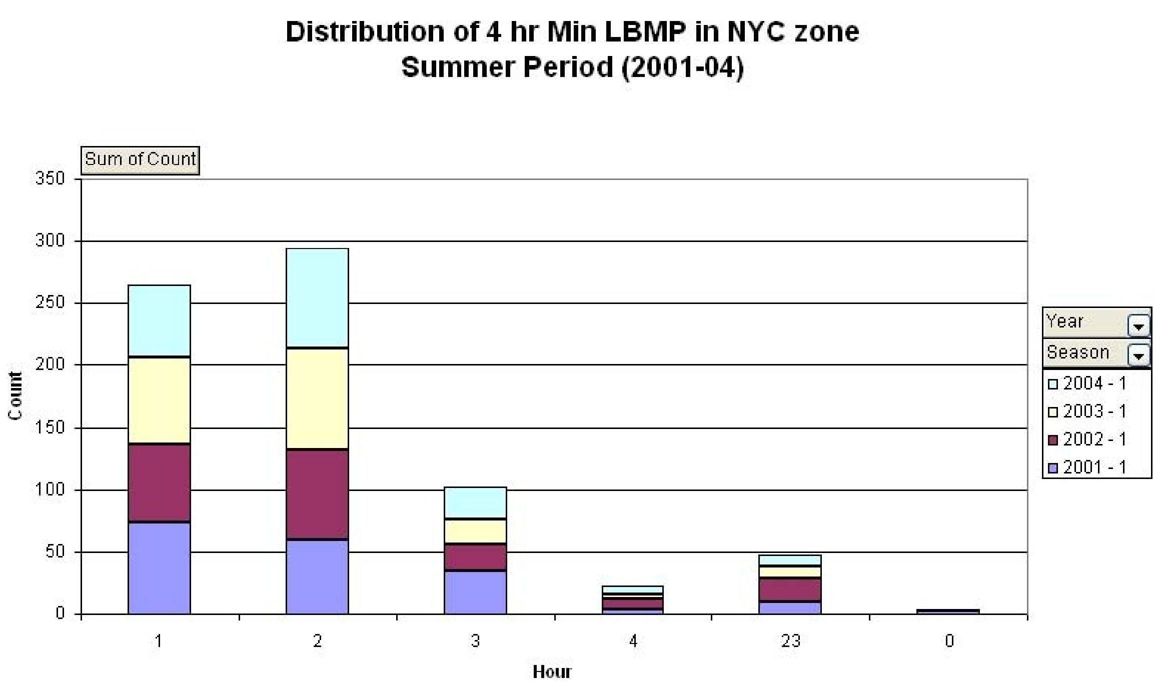


Figure 2-A5. Distribution of 4 Hour Minimum LBMP in NYC Zone Summer 2001-04

Appendix 2-A-4. Sensitivity Analysis for Financial Input Parameters of NPV for NaS Batteries for Energy Arbitrage

We performed a sensitivity analysis to determine the most important factors influencing the economics of NaS batteries for energy arbitrage in NYC. Table 2-A-7 summarizes the range of input parameters used for the sensitivity analysis.

Table 2-A7. Range for Financial Parameters Used for Sensitivity Analysis

Input Variable	Low	Base	High
T&D Benefits ($/kW-Year)	$-	$150	$300
Capital Cost ($/kW)	$1,500	$2,000	$3,000
Annual Revenues ($/MW)	$150,000	$250,000	$350,000
Charging Cost ($/MW)	$40,000	$60,000	$90,000
O&M Costs ($/kW-Year)	$20	$30	$50
Efficiency	65%	75%	85%
Discount Factor	5%	10%	15%

The base case had a NPV of -$225,000. Figure 2-A-6 shows the results of the sensitivity analysis as a tornado plot. Each bar indicates the variability in the NPV as a result of changing an individual factor. For example, the NPV will increase from -$225,000 to $700,000 if the installation can be used at a location that offers T&D benefits of $300 / kW-Year. Also the NPV will increase to $275,000 as compared to the base case if the capital cost is reduced to $1,500 /kW from the base case assumption of $2,000/kW.

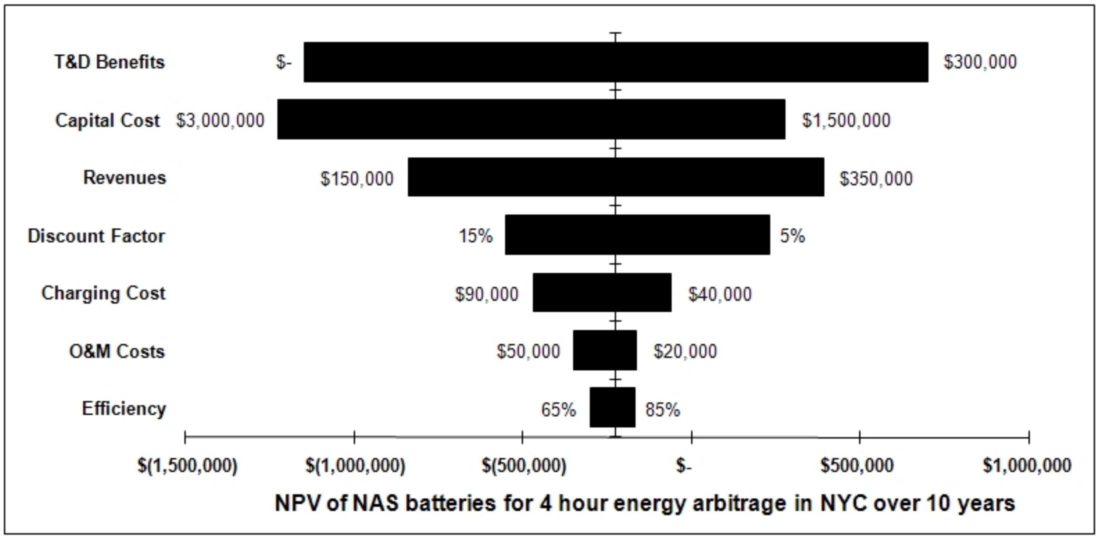


Figure 2-A6. Sensitivity Analysis for the Net Present Value (NPV) of NaS Installation for 4 Hours Energy Arbitrage in NYC

3: Economics of EES in PJM

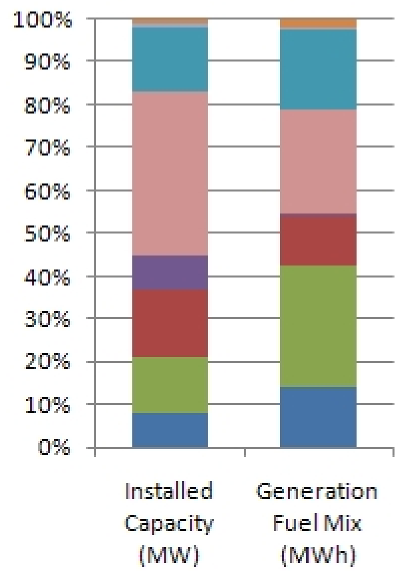
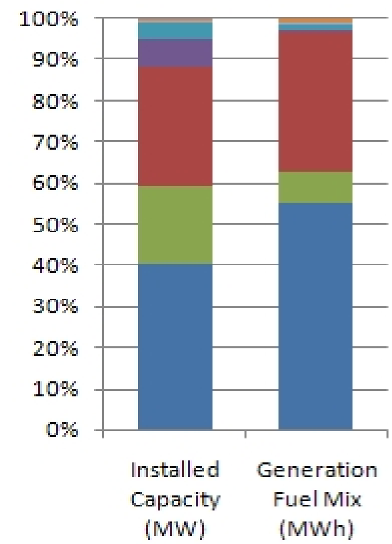
3-1. Introduction: PJM Electricity Markets and EES

As NYISO does, the PJM Interconnection offers opportunities for electric energy storage (EES) to participate in wholesale electricity markets. In this section, we quantify various revenue streams available to EES through PJM markets and compare the net present value of NaS batteries and flywheels for various applications.

The PJM Interconnection serves over 50 million people in the United States, has a peak load of 145,000 MW that it serves with 165,000 MW of generation, making it the world's largest electricity market. PJM's markets cover all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. (PJM, 2008a) PJM operates a Locational Marginal Price (LMP) based day-ahead and real-time energy market, a capacity market (using the Reliability Pricing Model), and ancillary service markets (regulation and synchronized reserve markets).

Table 3-1 provides a summary comparison of the PJM market with the NYISO market covered in Section 2. Figure 3-1 shows the geographical area covered by the PJM Interconnection and the locations of 17 zones within PJM. The 17 PJM zones are listed in Table 3-2. PJM underwent significant expansion during 2002-2005, so we have used the market results from 2005-2007 for evaluating the economics of EES in PJM markets to avoid drawing conclusions from transitional market behavior during the PJM expansion.

Table 3-1. Summary Comparison of NYISO and PJM Markets [4]

	NYISO	**PJM**
Established in	**1999**	**1997**
Population Served	19 Million	51 Million
States (All or parts of)	NY	DE, IL, IN, KY, MD, MI, NC, NJ, OH, PA, TN, VA, WV and DC
Generation Units	235+	1,270+
Transmission (Miles)	10,775	56,250
Peak Load (Pre 2006)	33.9 GW (32.1 GW)	144.6 GW (133.8 GW)
Generation Capacity	39.7 GW	164.6 GW
Capacity Reserves	5.8 GW (14.8%)	20.0 GW (12.2%)
2006 Average Real Time Energy Price	$70.9/MWh - $86.15/MWh	$50.07/ MWh
Generation Mix Other Wind Hydro Gas & Oil Oil Natural Gas Nuclear Coal		
Marginal Fuel	Natural Gas	Natural gas, Coal
Markets	• Energy: (Day Ahead, Hour Ahead, Real Time) • Capacity • Ancillary: ➢ Regulation ➢ Synchronized reserve ➢ Non Synch Reserve ➢ Operating Reserve	• Energy: (Day Ahead, Real Time) • Capacity • Ancillary: ➢ Regulation ➢ Synchronized reserve

[4] This summary was created based on data compiled from following sources: PJM 2008a, NYISO 2007, FERC 2007.

Table 3-2. PJM Zones

1. AECO	Atlantic Electric Co
2. AEP	American Electric Power Co *(joined PJM in May 2004)*
3. APS	Allegheny Power Systems (*joined PJM in Apr 2002)*
4. BGE	Baltimore Gas & Electric
5. COMED	Commonwealth Edison *(joined PJM in May 2004)*
6. DAY	Dayton Power and Light *(joined PJM in May 2004)*
7. DOM	Dominion *(joined PJM in May 2005)*
8. DPL	Delmarva Power & Light
9. DUQ	Duquesne Light *(joined PJM in Jan 2005)*
10. JCPL	Jersey Central Power & Light
11. METED	Metropolitan Edison Co
12. PECO	PECO Energy
13. PENELEC	Pennsylvania Electric Co
14. PEPCO	Potomac Electric Power Co
15. PPL	PPL Electric Utilities
16. PSEG	Public Service Electric & Gas Co
17. RECO	Rockland Electric Co *(joined PJM in March 2002)*

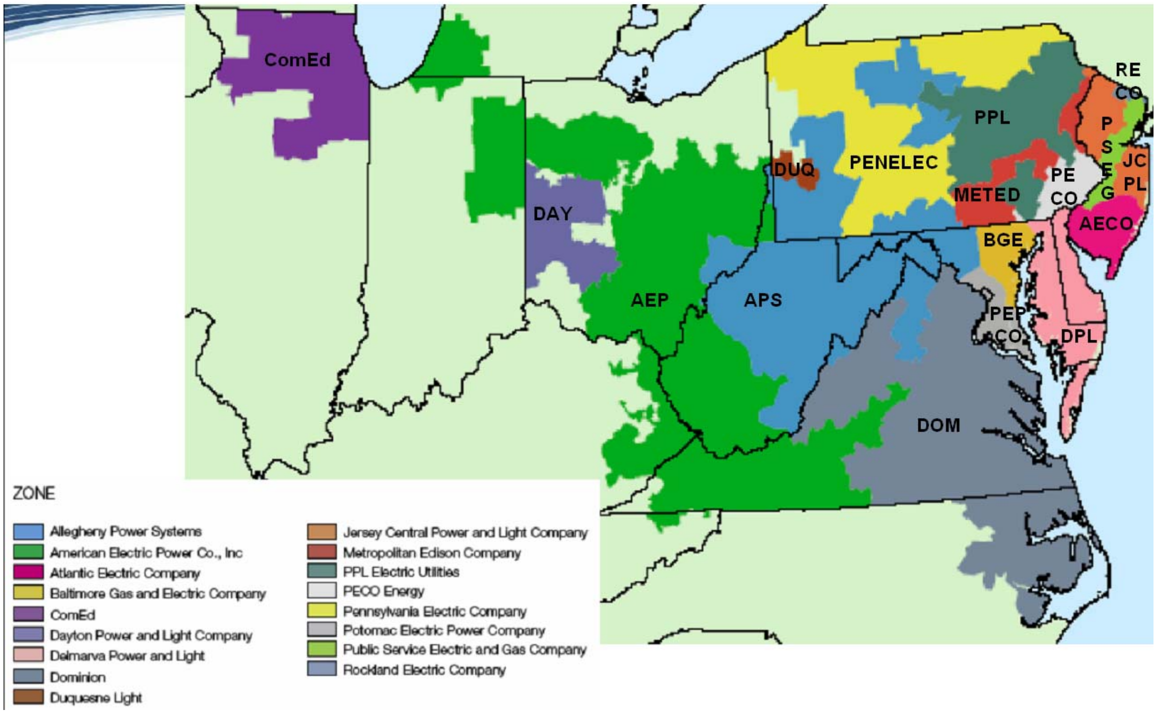


Figure 3-1. PJM Footprint and Zonal Map (Source: PJM 2007a)

3-2. Quantifying Revenue Potential for EES in PJM Markets

We have grouped these 17 zones into 4 super-zones based on a statistical analysis of energy market results (PJM 2008b), geographical considerations, and transmission constraints. Table 3-3 shows the results of the correlation analysis performed using hourly zonal energy prices for all 17 zones during 2006. The zones were grouped into super-zones based on a correlation coefficient of 0.98 or higher. The 4 super-zones are color coded to show the grouping used for further analysis.

The super-zones are:

- **PJM Central**: PENELEC and APS
- **PJM South**: BGE, PEPCO, and DOM
- **PJM West**: COMED, AEP, DAY, and DUQ
- **PJM East**: AECO, DPL, JCPL, METED, PECO, PPL, PSEG, and RECO

Table 3-3. Results of the correlation analysis to determine super-zones for PJM

	PEN ELEC	APS	BGE	PEP CO	DOM	COM ED	AEP	DAY	DUQ	AE CO	DPL	JCPL	MET ED	PECO	PPL	PS EG	RE CO
PENELEC	1.00																
APS	0.98	1.00															
BGE	0.94	0.95	1.00														
PEPCO	0.92	0.94	1.00	1.00													
DOM	0.93	0.94	0.99	0.98	1.00												
COMED	0.95	0.93	0.85	0.82	0.85	1.00											
AEP	0.96	0.94	0.87	0.84	0.87	0.99	1.00										
DAY	0.94	0.91	0.83	0.80	0.83	0.99	0.99	1.00									
DUQ	0.93	0.90	0.81	0.79	0.81	0.97	0.98	0.98	1.00								
AECO	0.95	0.95	0.97	0.96	0.95	0.87	0.88	0.85	0.83	1.00							
DPL	0.96	0.96	0.98	0.96	0.96	0.87	0.89	0.86	0.84	0.99	1.00						
JCPL	0.96	0.96	0.97	0.96	0.95	0.89	0.90	0.87	0.85	0.98	0.99	1.00					
METED	0.96	0.97	0.98	0.97	0.96	0.87	0.89	0.86	0.84	0.98	0.99	0.99	1.00				
PECO	0.96	0.96	0.97	0.96	0.95	0.88	0.89	0.86	0.84	0.99	0.99	0.99	0.99	1.00			
PPL	0.97	0.96	0.98	0.96	0.96	0.89	0.90	0.87	0.85	0.99	0.99	1.00	0.99	0.99	1.00		
PSEG	0.97	0.96	0.97	0.95	0.95	0.89	0.91	0.88	0.86	0.98	0.99	0.99	0.98	0.99	0.99	1.00	
RECO	0.97	0.96	0.95	0.94	0.94	0.89	0.91	0.88	0.87	0.97	0.98	0.98	0.97	0.98	0.98	1.00	1.00

Tables 3-A-1 to 3-A-6 in appendix provide the details of the regional distribution of the average peak and off-peak LMPs during 2005-2007 for all 17 PJM zones.

Figure 3-2 shows the average daily LMP curves for different seasons during 2005-06 for all 17 zones in PJM. In this figure the zones are grouped based on super groups for comparison of the daily LMP curves within each super-zone. The daily curve for each zone represents the average LMP for each hour of the day for the zone during the summer and winter of 2005 and 2006. Based on these LMP curves, PJM East and PJM South zones could have been grouped together, but we decided to use the 4 super-zones based on the correlation analysis as well as on expected capacity revenue differences (discussed later in section 3-4).

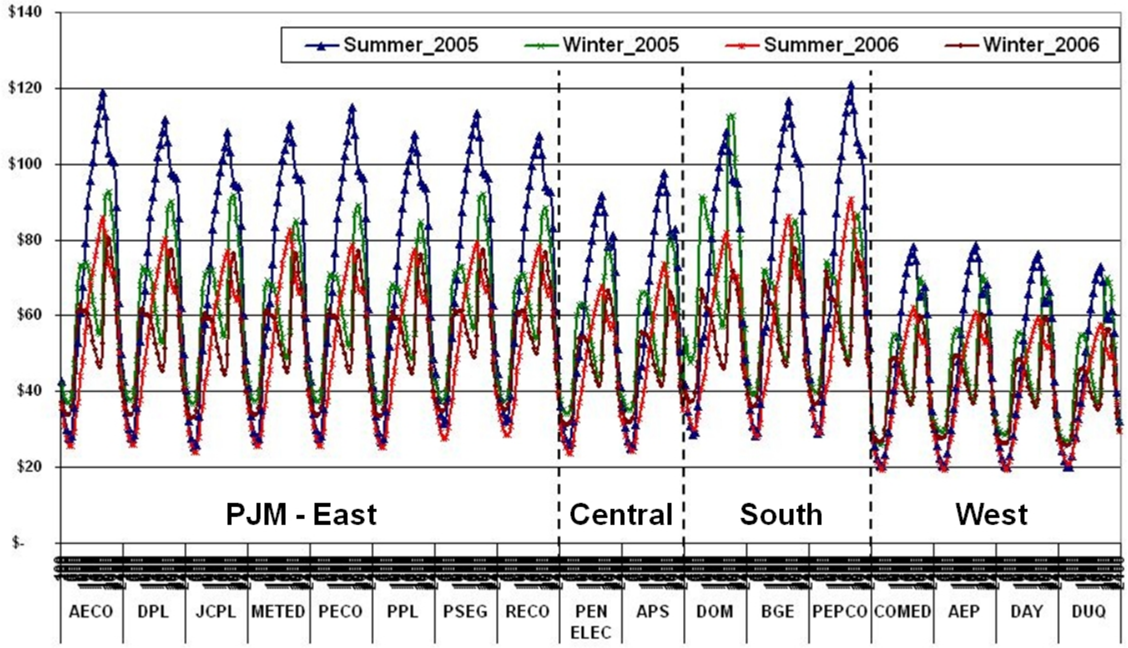


Figure 3-2. Average Daily LMP Curves from Energy Market for Summer and Winter 2005-2006 for All PJM Zones

The grouping of the 17 PJM zones into 4 super-zones is also supported by transmission constraints as shown in Figure 3-3. Figure 3-4 shows the geographical grouping of the 4 super-zones selected for analysis. The PJM East super-zone includes zones that are north and east of the central interface; the PJM Central super-zone includes zones that are influenced by the western interface and the PJM South super-zone includes zones that are located south of the central interface. The PJM West super-zone includes regions dominated by area with coal plants.

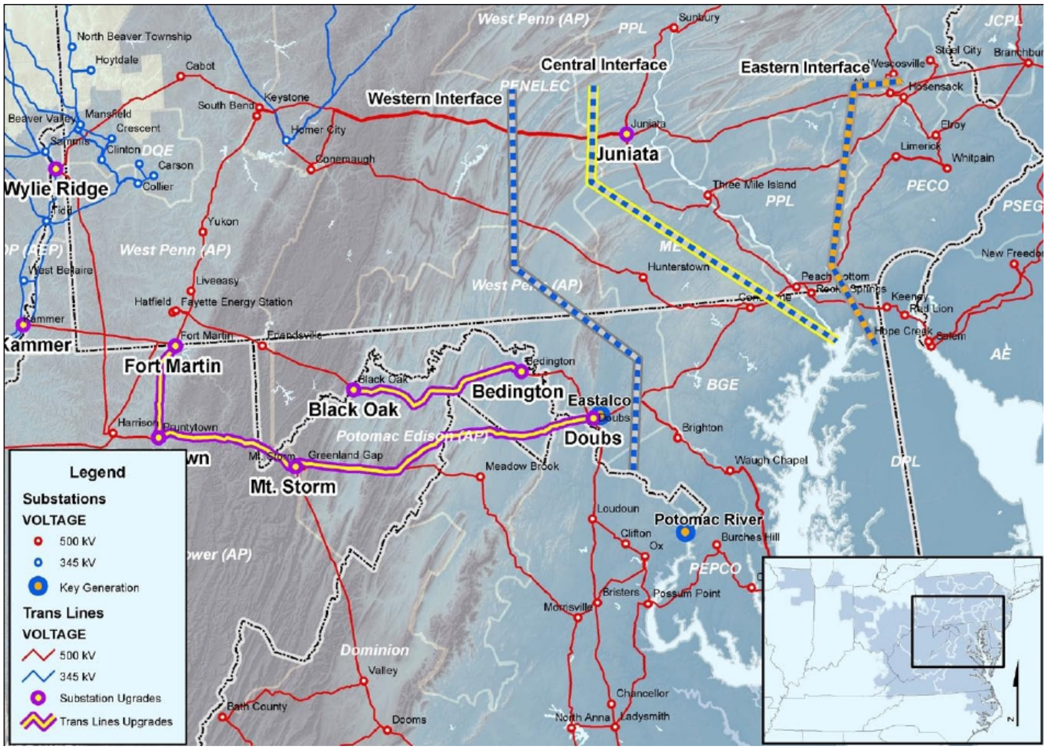


Figure 3-3. PJM Transmission Interfaces (Source: PJM 2007a)

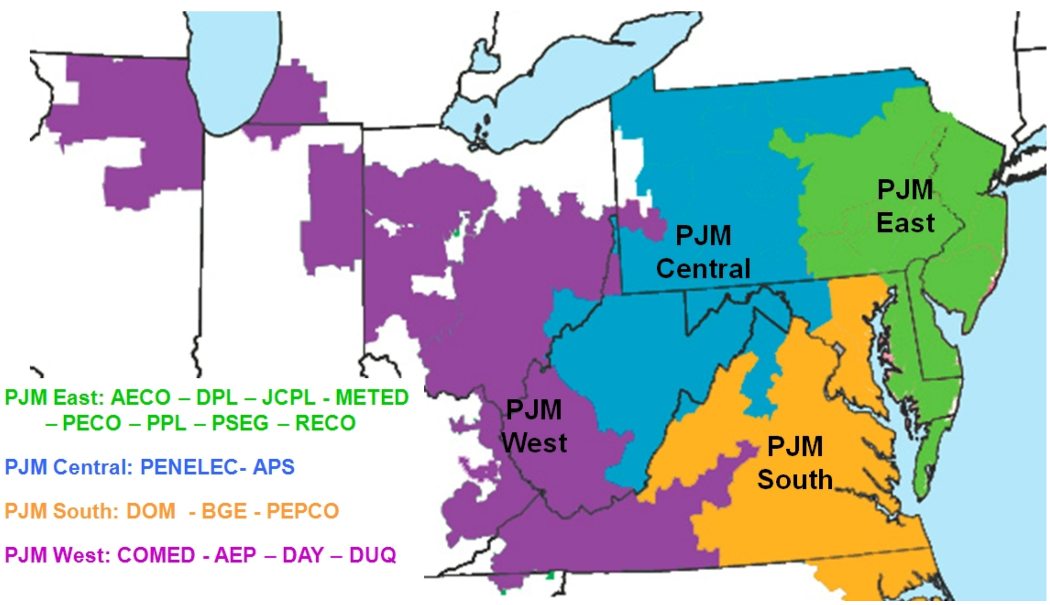


Figure 3-4. PJM Super-Zones Used in This Analysis

These 4 super-zones were used for identifying the various revenue streams for NaS batteries and flywheels in the PJM markets. The revenue streams available for EES in PJM include:

- Energy arbitrage through participation in day-ahead and real-time energy markets
- Capacity revenues under the Reliability Pricing Mechanism (RPM) model
- Ancillary service market revenues for providing regulation and/or synchronized reserves

Based on the technical characteristics of flywheels and NaS batteries, this research evaluated the economics of using flywheels for providing regulation and NaS batteries for providing energy arbitrage and synchronized reserves in the PJM electricity market. The analytical framework used for quantifying the revenue streams is described in section 2-4 and the binding constraints are discussed in Appendix 2-A-2.

3-3. Energy Arbitrage

The hourly electricity markets (day-ahead and real-time) in PJM provide opportunities for EES technologies such as NaS batteries to participate in the energy markets and capture the energy arbitrage revenue. While average hourly electricity prices in PJM's real time market ranged between \$49/MWh and \$58/MWh during 2005-2007, peak prices went above \$100/MWh for 1100, 470, and 780 hours respectively, during 2005, 2006, and 2007. Figure 3-5 shows the price duration curves for PJM's real-time energy market during 2005-2007.

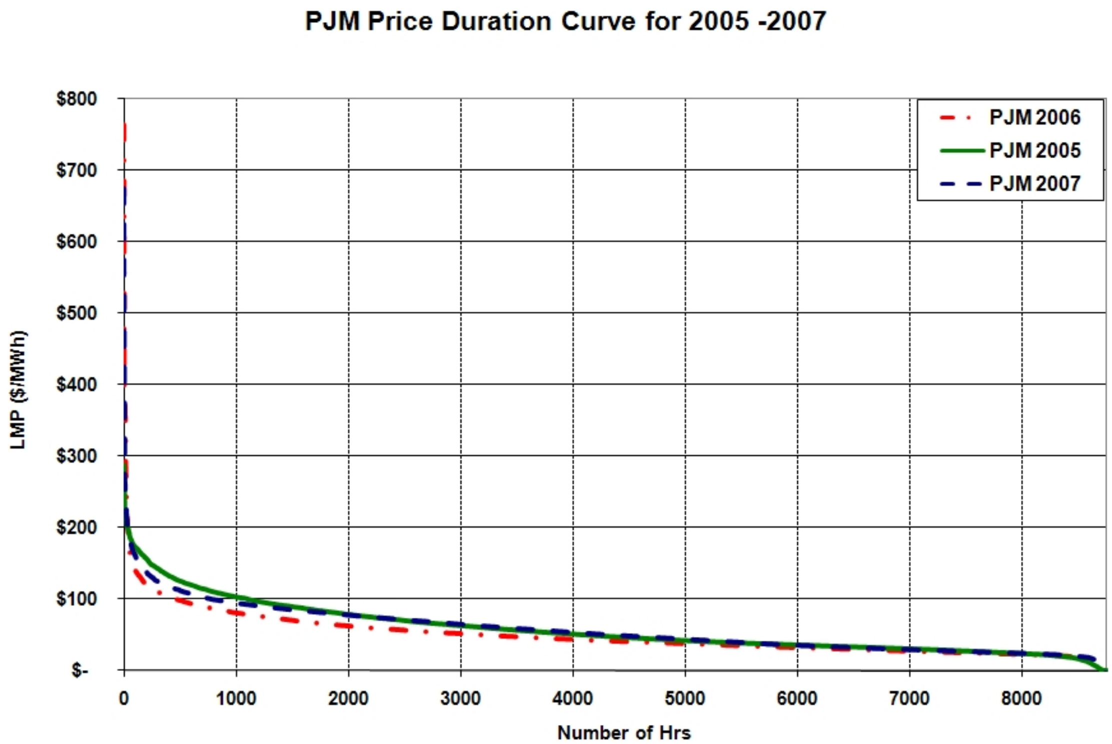


Figure 3-5. PJM Real-Time Price Duration Curve for 2005-2007

3-3-1. Quantifying Energy Arbitrage Revenue Potential in PJM

For the four PJM super-zones, we have quantified the energy arbitrage revenue potential for 2-hour, 4-hour, and 10-hour discharge periods. The first step in quantifying the energy arbitrage revenue was to identify the period for maximum revenue and the period for minimum charging cost for different energy arbitrage durations. Table 3-4 summarizes the analysis performed to determine operating hours for 2-hour, 4-hour, and 10-hour energy arbitrage operation by capturing the seasonal patterns for the highest-priced on-peak revenue period and the lowest-cost off-peak period. The analysis methodology is similar to one described in appendix 2-A-3.

As shown in Table 3-4, there is a clear shift in the maximum revenue period during the summer capability months (May 1 to October 31) and the winter capability months (Nov 1 to April 30). The lowest cost period does not reflect such seasonal shift. Figures 3-A-1, 3-A-2, and 3-A-3 in the Appendix show the details of results for analysis conducted to determine operating period for the 4-hour energy arbitrage.

Table 3-4. Summary of Analysis for Determining Operating Hours for Energy Arbitrage

	Max Revenue Period		Min Charging Cost period
	Summer	**Winter**	**Annual**
2 Hr Operation	**16:00 - 17:00**	**18:00 - 19:00**	**3:00 - 4:00**
4 Hr Operation	**15:00 - 18:00**	**18:00 - 21:00**	**2:00 - 5:00**
10 Hr Operation	**12:00 - 21:00**	**13:00 - 22:00**	**23:00 - 8:00**

** PJM uses the convention of hour ending with to define all operating hours*

Using these operating hours, the annual net revenues for energy arbitrage were calculated. Table 3-5 shows the summary of annual net revenues (thousand $/ MW) generated in different zones for 2-, 4-, and 10-hour energy arbitrage using 2005-2007 energy market data. These results are based on round-trip efficiency of 0.75 for the NaS battery.

Table 3-5. Summary of the Annual Net Revenue for Energy Arbitrage

(2005- 2007)

	PJM East (PECO)			PJM South (BGE)			PJM Central (PENELC)			PJM West (AEP)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
10 Hr	$ 59	$ 76	$ 107	$ 59	$ 72	$ 101	$ 49	$ 64	$ 80	$ 49	$ 66	$ 77
4 Hr	$ 51	$ 63	$ 80	$ 53	$ 64	$ 77	$ 42	$ 52	$ 62	$ 40	$ 50	$ 57
2 Hr	$ 28	$ 34	$ 44	$ 29	$ 35	$ 41	$ 22	$ 27	$ 33	$ 20	$ 26	$ 29

3-3-2. Effect of Round-Trip Efficiency on Energy Arbitrage Revenues

Since the EES technologies considered for this analysis are yet to be fully commercialized, we performed additional sensitivity analysis to determine the effect of round-trip efficiency on the net revenue potential for energy arbitrage in the four super-zones. Currently most of the manufacturers state that their EES technologies can offer round-trip efficiencies of 70%-85%. Figures 3-6, 3-7, 3-8, and 3-9 show the result of an analysis conducted to calculate the effect of round-trip efficiency on net revenues (i.e., the difference between on- peak revenues and off-peak charging costs) from energy arbitrage during 2005-2007.

Lower round-trip efficiencies result in higher charging costs due to additional charging time required to cover the losses. These results show a switchover point at around 73% round-trip efficiency where the 4-hour arbitrage results in higher net revenues than the 10-hour energy arbitrage operations for three of the four super-zones (PJM East, PJM Central, and PJM South). This analysis indicates that if the EES unit had round-trip efficiency less than 73%, the market participant operating in the PJM East, Central, or South region would have earned higher net revenues by operating the unit for four hours than its net revenues for 10 hours of operation during 2005-2007. For PJM West this switchover point occurs at 69% round-trip efficiency and for a round-trip efficiency of approximately 60%, even 2 hour energy arbitrage would have resulted in higher net revenues than 10 hour operation. This switchover point between 2 hour and 10 hour operation occurs at a round-trip efficiency of ~ 65% for PJM East, Central, and South regions.

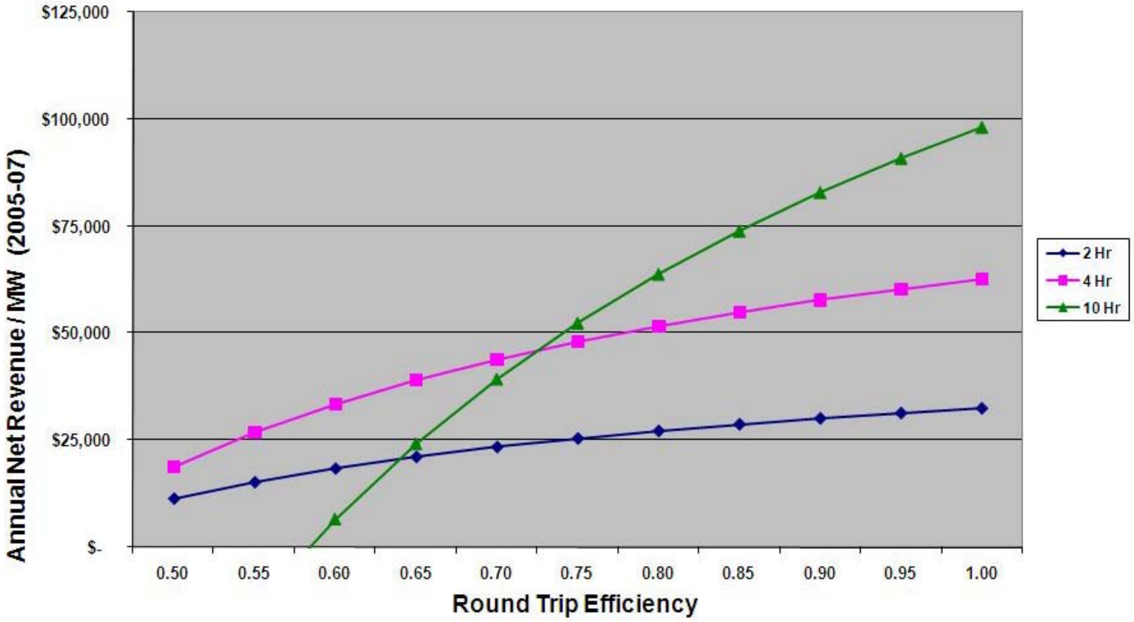


Figure 3-6. Effect of Round-Trip Efficiency on Annual Net Revenues from Energy Arbitrage for PJM Central (PENELEC)

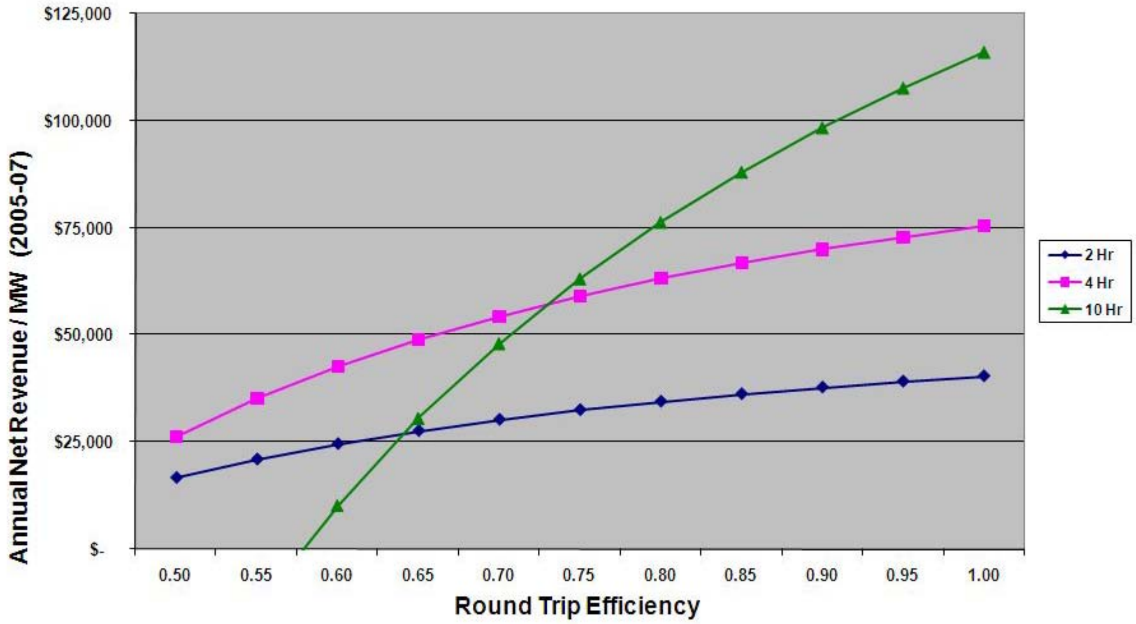


Figure 3-7. Effect of Round-Trip Efficiency on Annual Net Revenues from Energy Arbitrage for PJM East (PECO)

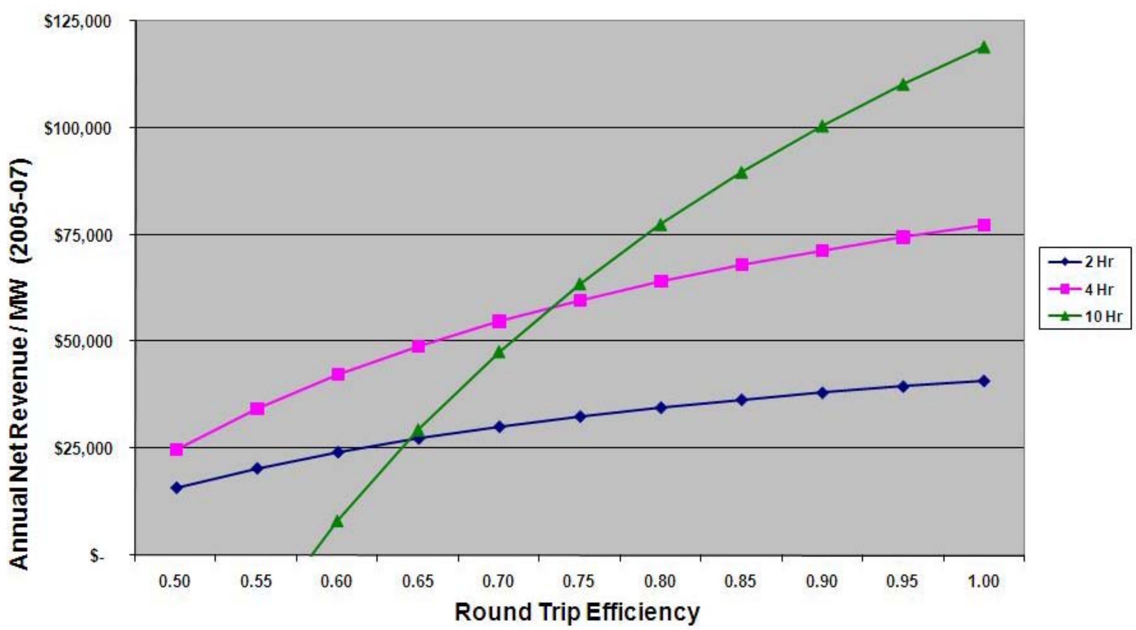


Figure 3-8. Effect of Round-Trip Efficiency on Annual Net Revenues from Energy Arbitrage for PJM South (BGE)

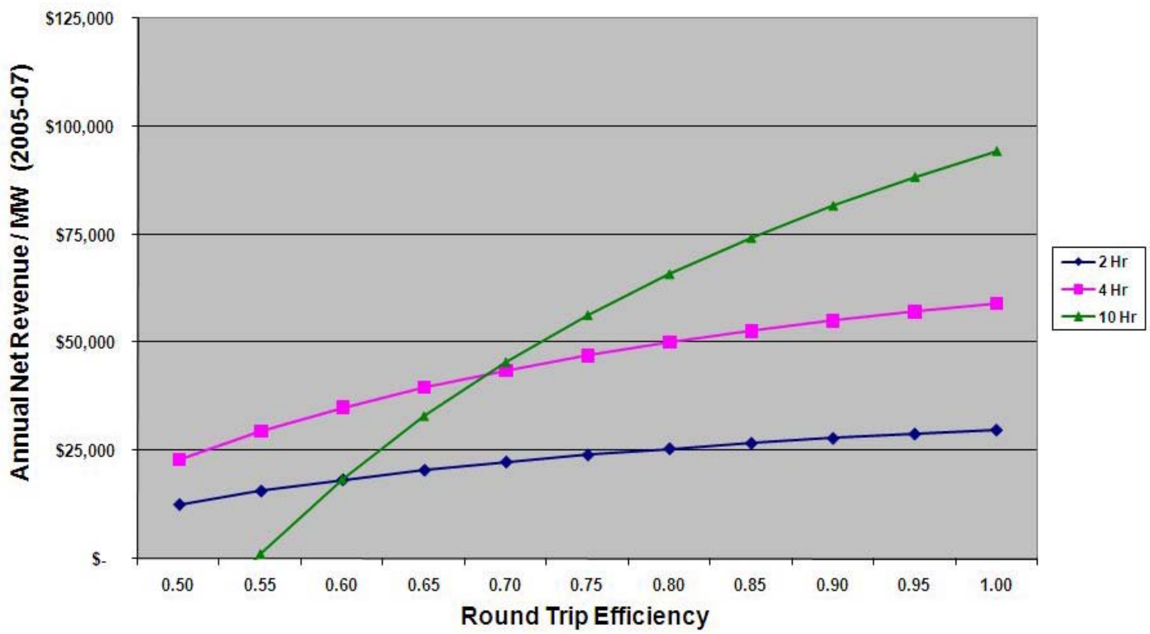


Figure 3-9. Effect of Round-Trip Efficiency on Annual Net Revenues from Energy Arbitrage for PJM West (AEP)

3-4. Capacity Market Revenues

In addition to energy arbitrage revenues, NaS batteries can also receive capacity payments from PJM. PJM has two capacity markets (daily and long-term). Until 2007, PJM had a single price for capacity resources located anywhere in the PJM territory. Table 3-6 provides a summary of load-weighted average capacity prices based on transactions in various capacity auctions (daily and long-term) held by PJM from 1999-2006 (2008a).

Table 3-6. Summary of capacity auction results for PJM (1999-2006)

Year	$/ MW-Day	$/MW-Year
1999	$52.24	$19,068
2000	$60.55	$22,101
2001	$95.34	$34,799
2002	$33.40	$12,191
2003	$17.51	$6,391
2004	$17.74	$6,475
2005	$6.12	$2,234
2006	$5.73	$2,091

PJM recently restructured the capacity markets by introducing locational capacity markets as part of the Reliability Pricing Model (RPM) that was approved by FERC in 2007 (PJM 2007b). Table 3-7 shows 2007-2008 and future anticipated prices for capacity under RPM for representative zones within the four super-zones (PJM 2008c). Since historic capacity prices are no longer applicable, the range of annual capacity prices from Table 3-7 was used in calculating the total revenue potential for energy arbitrage in the different regions.

Table 3-7. Summary of Capacity Auction Results for PJM Under RPM **(PJM 2008c)**

		2007-08	2008-09	2009-10	2007-08	2008-09	2009-10
Zone	**Super-zone**	**Preliminary Zonal Capacity Price [$/MW-day]**			**Preliminary Zonal Capacity Price [$/MW-Year]**		
BGE	**PJM South**	**$188.05**	**$210.11**	**237.33**	**$68,639**	**$76,690**	**$86,625**
PECO	**PJM East**	**$197.16**	**$148.80**	**191.32**	**$71,963**	**$54,312**	**$69,832**
PENLC	**PJM Central**	**$40.69**	**$111.92**	**191.32**	**$14,853**	**$40,851**	**$69,832**
AEP	**PJM West**	**$40.69**	**$111.92**	**102.04**	**$14,853**	**$40,851**	**$37,245**

3-5. Ancillary Service Revenues

As discussed in section 1-5, PJM markets allow EES resources to provide ancillary services. Currently EES can participate in ancillary service markets operated by PJM: regulation and synchronized (or spinning) reserve. Regulation service helps PJM maintain the stability of the power system in order to correct short-term changes (within 5 minutes) in load and supply. Synchronized reserves are used in case of unexpected power requirements within 10 minutes.

3-5-1. Regulation Revenues

Regulation service is traditionally accomplished by committing online generators whose output can be raised or lowered, usually in response to an Automatic Generation Control (AGC) signal, as necessary to follow changes in load. The control signal is generated every six seconds. PJM requires a regulation resource to respond to the regulation signal within five minutes. The regulation requirement is 1% of peak load in PJM (PJM 2007c). As shown in Figure 3-10, PJM integrated various regulation control zones into a single regulation market region in August 2005.

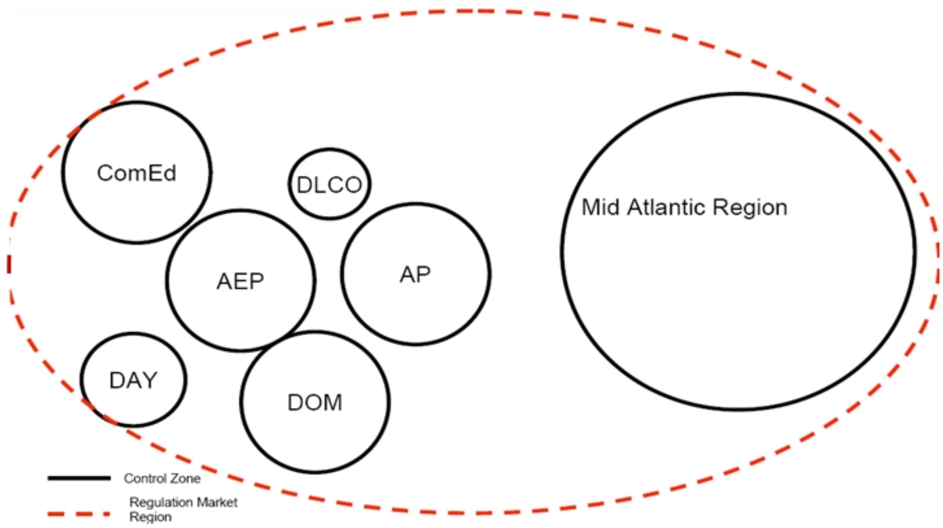


Figure 3-10. PJM Single Regulation Market Region (Source: PJM 2007c)

In PJM, the regulation price offers are capped at $100/MWh, but the generators are also eligible to receive additional payment for opportunity cost. The opportunity costs are paid to generators dispatched by PJM for regulation in 2 scenarios: If the generator has to increase its output when LMP is lower than the energy bid price for the generator (i.e. uneconomical operation) or if the generator is required to lower its output when LMP is greater than the bid price (i.e. lost revenue).

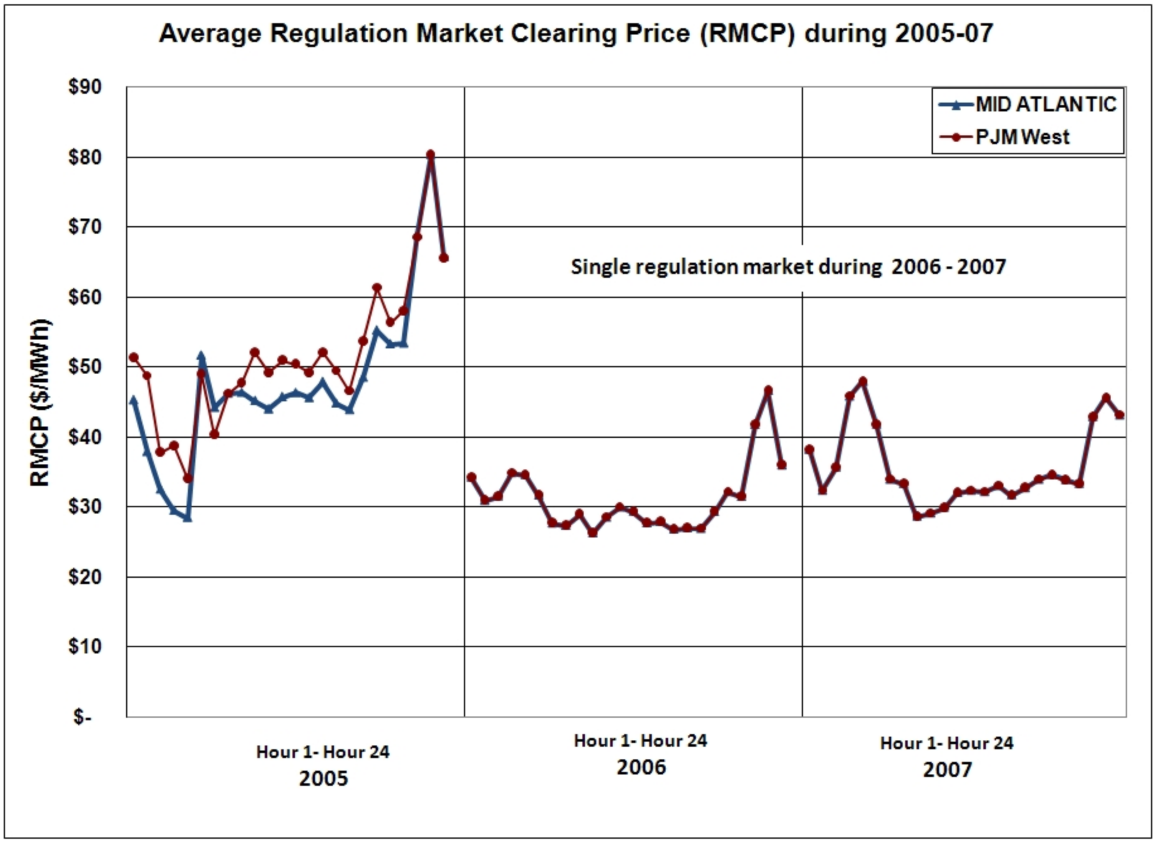


Figure 3-11. PJM Regulation Market Clearing Price Curves (2005-2007)

Figure 3-11 shows the average daily prices curves for the regulation market clearing price (RMCP) for during 2005-2007. We have used the hourly RMCP prices during 2005-2007 to quantify the revenue potential for using flywheels to provide regulation service. While calculating the net revenue potential for regulation, a 15% energy penalty was deducted from the regulation revenues to cover round-trip and standby losses of the flywheels.

It is important to note that several issues may affect the revenue potential for regulation services in PJM markets in the future.

- Although traditionally it is expected that regulation service is a net energy zero service and the regulation signal will move in both directions (positive and negative), PJM recently has indicated that it may require the regulation signal to go in the same direction for longer duration.[5] This could result in an energy-limited resource such as a flywheel reaching the technical limit (either fully charged or fully discharged) for a considerable amount of time. Based on the sample regulation signal (for the first

[5] Based on personal communication with the PJM Market Support team and Mr. Ken Huber, Manager, Advanced Technology at PJM Interconnection.

week of June 2006) provided by PJM[6], a flywheel would be able to provide regulation for only 58% of the time due to its energy-limited nature (15-minute duration). Under current market rules PJM will not penalize the flywheel for noncompliance if the noncompliance is a result of technical limitation. The test results from Beacon Power's demonstration project in California and New York indicate that flywheels have complied with the Area Control Error (ACE)[7] signal in respective control zones more than 90% of the time. At the same time, there is no certainty that a flywheel would be able to receive full regulation revenues or that the revenues would be pro-rated based on future compliance.

- The other issue related to regulation revenue for flywheels is based on the way PJM provides payments for regulation costs. As mentioned earlier in this section, generators are eligible to receive opportunity cost payments (based on lost revenue from the energy market) in addition to the RMCP payments. Under current rules, non-capacity resources such as flywheels that do not supply an energy bid are not eligible to receive opportunity cost payments for providing regulation. Figure 3-12 shows the average RMCP and opportunity cost payments from the regulation market results for the period from August 2005 to February 2008. Based on these results it can be argued that the RMCP does not reflect the true price of regulation in PJM. For example, the average RMCP price for December 2007 was $26.96/MWh, but at the same time PJM also paid for suppliers' opportunity cost, that resulted in an average additional payment of $23.41/MWh. This could provide generators an opportunity to suppress the regulation revenues that can be received by new technologies such as flywheels, by lowering the bids for regulation services and recovering costs through opportunity costs and reducing the revenue potential of flywheels.

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[6] Sample regulation signal for the first week of June 2006 is available at http://www.pjm.com/markets/ancillary/downloads/regulation-signals.xls

[7] ACE represents the instantaneous balance of power flow within the control area. PJM uses regulation to control ACE by deriving the regulation signal from ACE for different control zones.

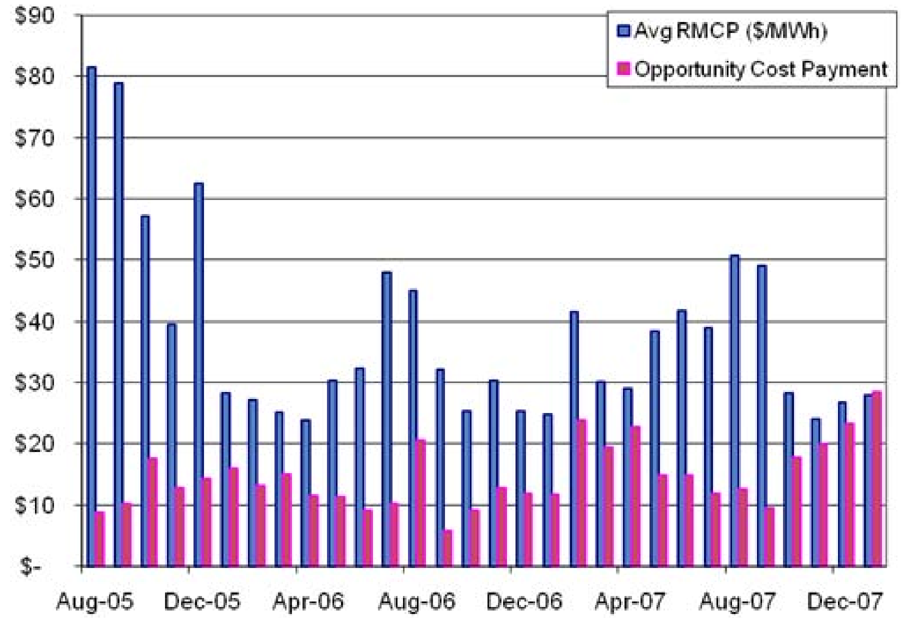

Figure 3-12. Average RMCP and Opportunity Cost Payments in Regulation Markets from Aug. 2005 to Feb. 2008 (PJM, 2008e)

3-5-2. Synchronized Reserve Revenues

Synchronized reserves are used to provide compensation for a sudden loss in generation or transmission. Synchronized reserves must respond within 10 minutes and must be synchronized with the grid. PJM rules allow EES and demand response resources to participate in reserve markets as long as they have real-time telemetry in place and the resource can be directly dispatched by PJM (PJM 2007c).

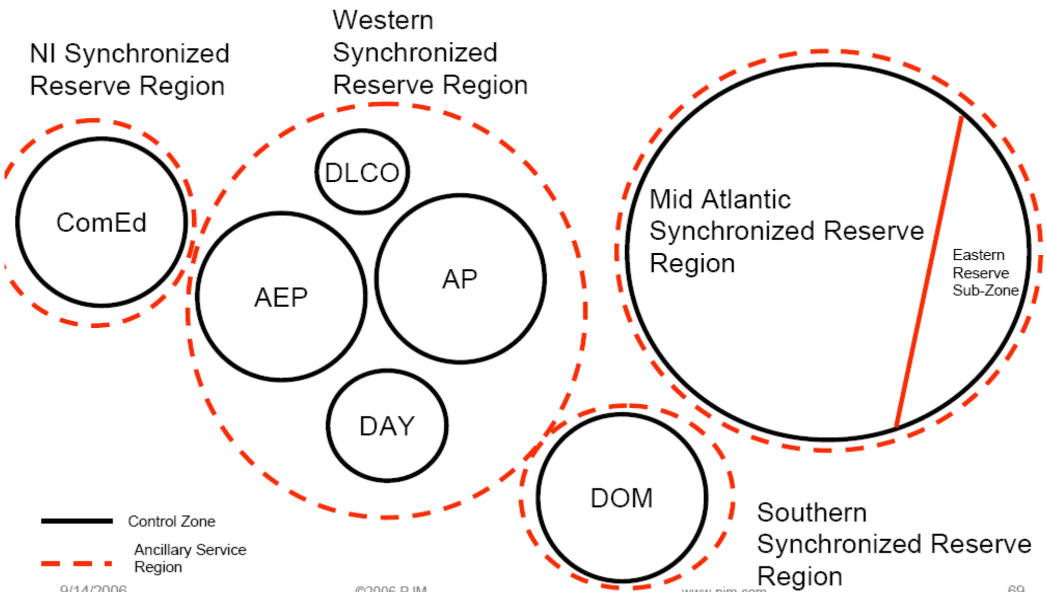

Figure 3-13a. PJM Synchronized Reserve Market Regions Prior to 2007 (Source: PJM 2007c)

As shown in Figure 3-13a, PJM formerly operated four different regions for synchronized reserves: the Northern Illinois Synchronized Reserve region, Western Synchronized Reserve region, Southern Synchronized Reserve Region, and Mid Atlantic Synchronized Reserve region. These regions were unified (except for the Southern region comprising the Dominion zone) in a single market in early 2007 as shown in Figure 3-13b.

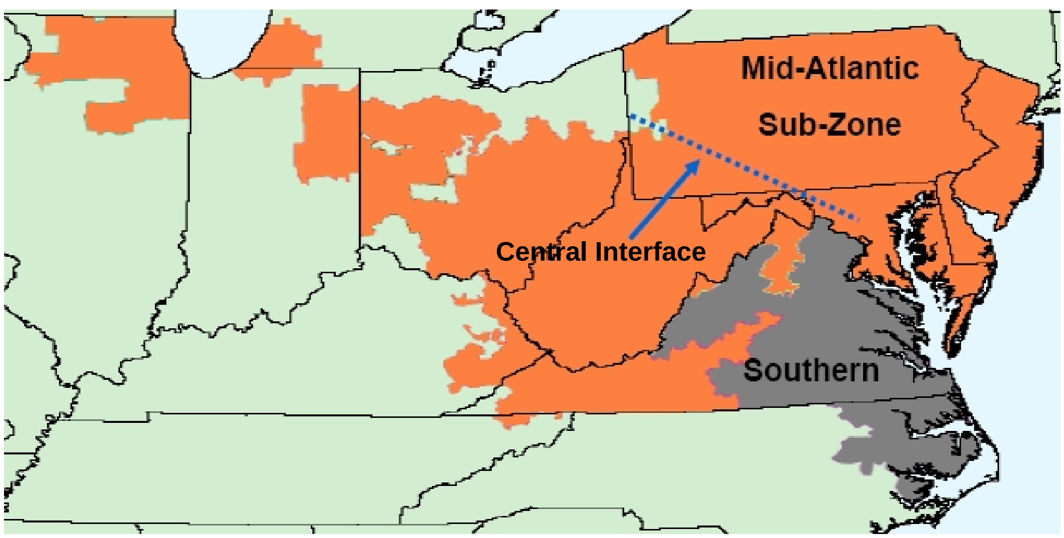

Figure 3-13b. PJM Synchronized Reserve Market Zones Since 2007 (Source: PJM 2007c)

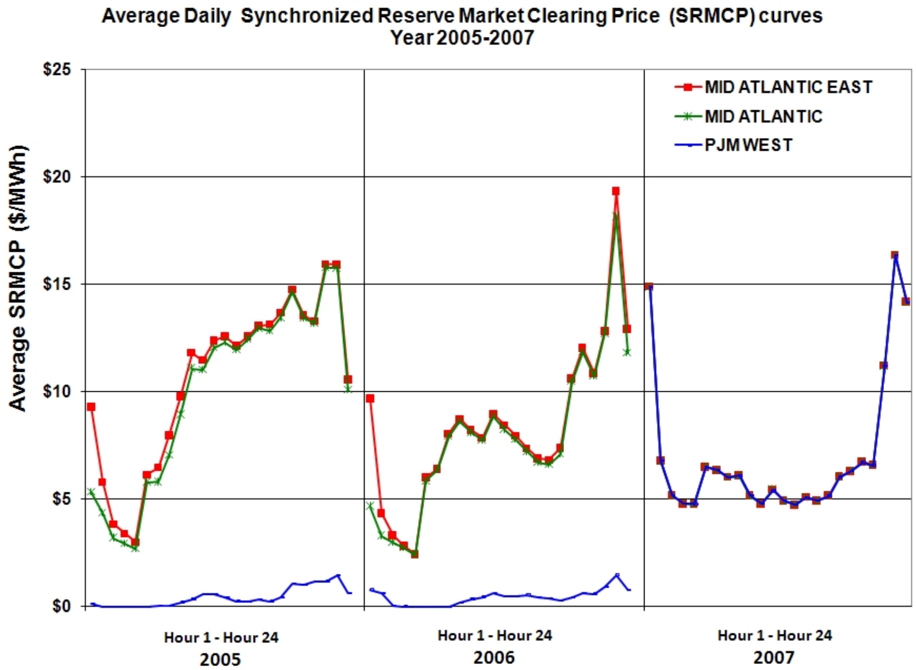

Figure 3-14. PJM Synchronized Reserve Market Clearing Price (2005-07) (PJM, 2008f)

Figure 3-14 shows the daily synchronized reserve market clearing price (SRMCP) curves for 2005-2007 period. For year 2007, all the representative zones considered in this analysis were part of the unified PJM region and thus had same market clearing price for synchronized reserves.

NaS batteries can be used for providing synchronized reserves when not used for discharging or charging. Flywheels cannot receive synchronized reserve revenues, as PJM does not allow a unit to bid in both regulation and synchronized reserve market simultaneously (PJM 2007c). Thus we have used 15 hours of synchronized reserve revenues to supplement the 4-hour energy arbitrage revenue (the remaining 5 hours are used for charging the battery).

3-6. Estimating Annual Net Revenues for Different Applications

As discussed previously, NaS batteries can provide energy arbitrage, synchronized reserves, and capacity reserves, while a flywheel can provide regulation. Thus we have quantified annual net revenue potential for the following applications:

- NaS battery
    - Energy arbitrage (10 hours) + capacity reserve
    - Energy Arbitrage (4 hours) + synchronized reserve (15 hours) + capacity resource
- Flywheel
    - Regulation (24 hours)

Table 3-8 provides a summary of the net revenues that could be obtained by the EES operators in the PJM markets.[8] The minimum net revenues are for the year 2006, the maximum net revenues are for the year 2005, and the average revenues are calculated based on the average net revenues for 2005-2007.

Table 3-8. Summary of Annual Net Revenue Potential (based on 2005-2007 market data)

Application	Expected Net Revenues (Thousand$/ Year)											
	PJM East (PECO)			PJM South (BGE)			PJM Central (PENELC)			PJM West (AEP)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy Arbitrage* (10Hours)	$89	$116	$141	$103	$124	$152	$43	$78	$118	$44	$78	$90
Energy Arbitrage* (4 Hours) + Synch Reserve (15 Hours)	$140	$177	$207	$155	$185	$218	$91	$138	$188	$53	$96	$127
Regulation (24 Hours)	$205	$255	$333	$201	$252	$332	$213	$266	$346	$219	$276	$389

* includes capacity revenues through RPM.

These results indicate that the PJM South region offers the highest potential for net revenues for NaS batteries, followed by PJM East and PJM Central. PJM West provides the lowest revenue opportunity for NaS batteries. Although PJM regulation offers the same regulation revenues for the entire territory, the PJM West region offers the best opportunity for using flywheels for regulation due to the lower cost for energy required to compensate for losses during regulation.

[8] *The differences in energy arbitrage net revenues across NYISO zones and PJM zones can be explained by observing the differences in capacity revenues as well as the differences in the average daily LMP curves over 2001-2007 shown in Figure A-3-5 in the Appendix.*

3-7. Net Present Value (NPV) Analysis

As shown in Table 3-8, the expected net revenues for EES resources can vary from year to year. This uncertainty, that is due to fluctuations in energy prices, is incorporated into the analysis by performing a Monte Carlo simulation to calculate the net present value of both a NaS battery and a flywheel across all four regions over a 10-year period. This simulation was performed for 1,000 iterations using a triangular distribution for the net revenue for 4-hour energy arbitrage combined with 15 hours of synchronized reserve for NaS batteries in all four regions. Using a triangular distribution of net revenue from regulation, similar simulations were also performed for flywheels. The minimum, maximum, and average values for net revenue were selected for each region based on the data presented in Table 3-8. Based on the explanation provided in section 2.8, additional benefits were valued at $150/kW-year for NaS installations (considering both reliability and power quality benefits) and $100/kW-year for flywheel installations (by considering only the power quality benefits). Additional simulations were run to quantify the effect of the estimated capital cost on the NPV of both a NaS battery installation (in PJM south) and a flywheel installation (in PJM West). Table 3-9 provides a summary of all the financial parameters used in the NPV simulations.

Table 3-9. Summary of Financial Parameters

	NaS Battery	**Flywheel**
Capital Cost ($/kW)	$1,500-$2,000-$3,000	$750-$1,500-$2,000
O&M Cost ($/kW-yr)	$30	$25
Disposal cost ($/kW)	$15	-
Round-trip Efficiency	75%	85%
Discount factor	10%	10%

The simulation results shown in Figure 3-15 indicate that flywheels have an expected positive NPV for the complete range of capital cost estimates. There is a 50% probability that the NPV would be at least $770,000 for the average capital cost estimate of $1500/kW. The mean NPV would increase to over $1,500,000 if the capital cost drops to $750 /kW. The mean NPV drops to approximately $275,000 if the capital cost is $3000/kW.

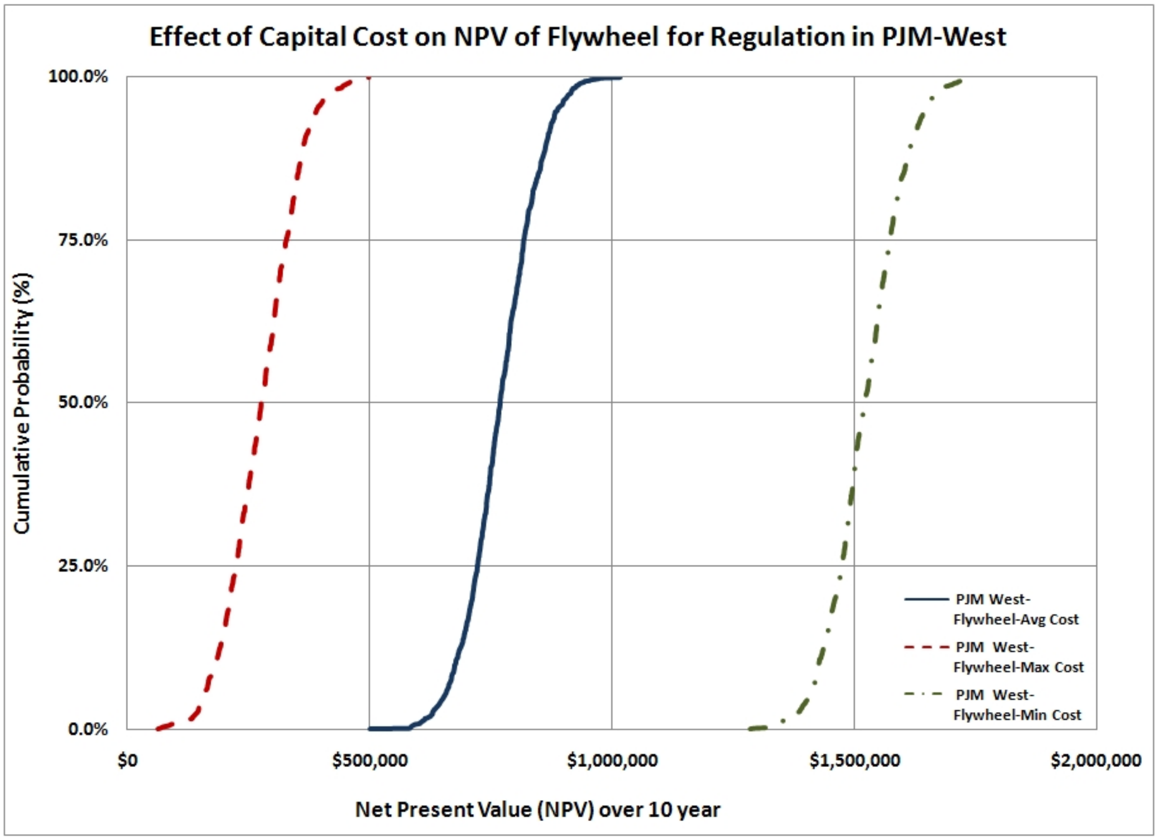

Figure 3-15. Effect of Capital Cost on NPV of Flywheels for Regulation in PJM-West

When the average capital cost estimate was used to simulate the NPV of using flywheels across the four PJM regions, the mean NPV was approximately $565,000 for PJM South, $580,000 for PJM East, and $650,000 for PJM Central, as shown in Figure 3-16. The highest revenue potential was obtained in PJM West with a mean NPV of $770,000.

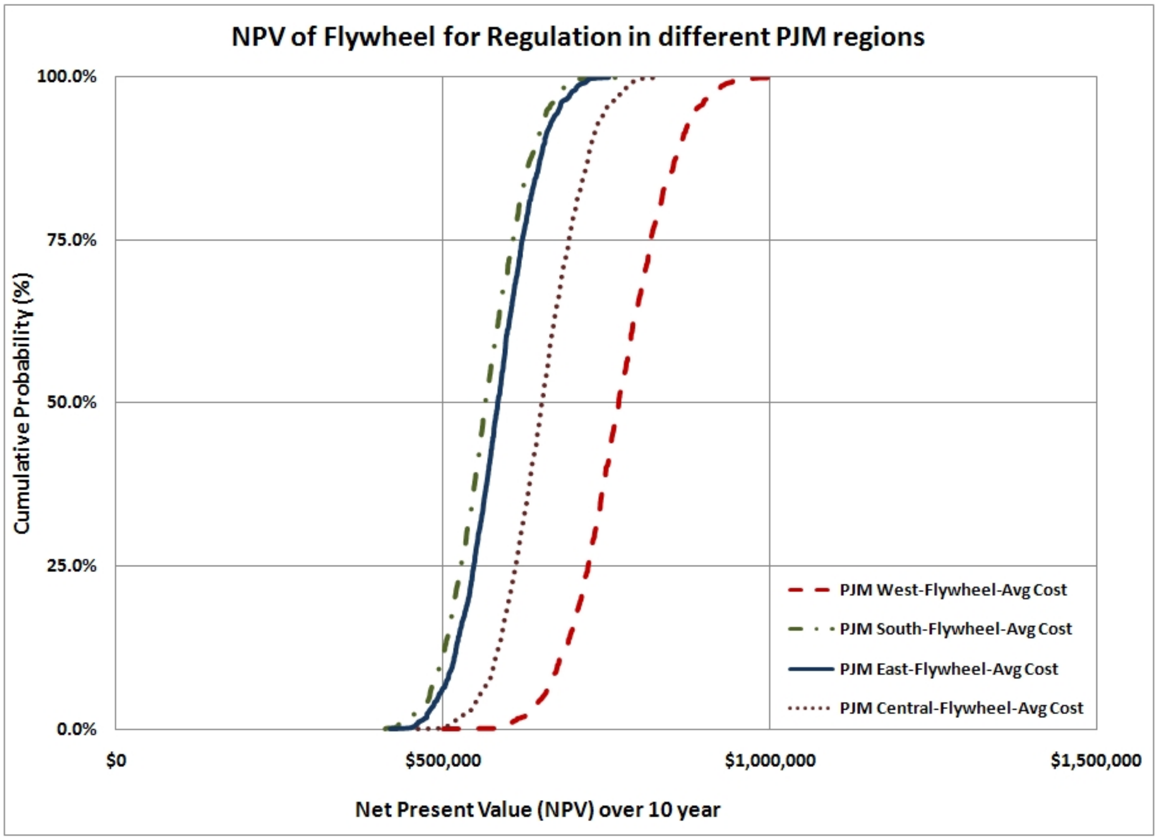

Figure 3-16. NPV of Flywheels for Regulation in Different PJM Regions for Average Capital Cost

Similar simulations were conducted to evaluate the NPV of NaS batteries for providing energy arbitrage (4 hours) and synchronized reserve (15 hours), that offered the maximum net revenues for NaS batteries.

When the average capital cost estimate of $2,000 /kW for a NaS battery installation was used to calculate the NPV in all 4 regions of PJM, the NPV was negative for all cases as shown in Figure 3-17. The mean NPV for PJM South was -$140,000; for PJM East the mean NPV was -$215,000. The mean NPV for PJM Central dropped down to -$430,000. The PJM West region had the lowest mean NPV of -$720,000.

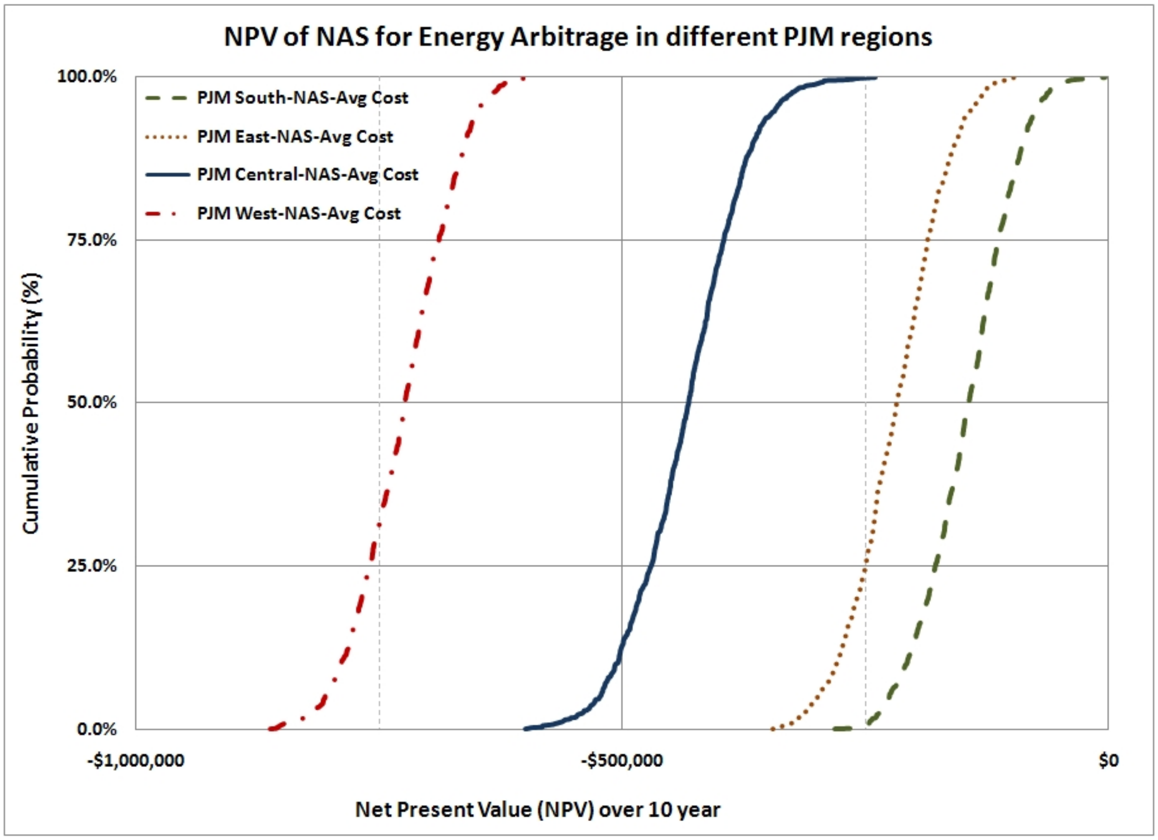

Figure 3-17. NPV of NaS for Energy Arbitrage and Synchronized Reserve in Different PJM Regions for Average Capital Cost

A sensitivity analysis was performed by modifying the assumption for the capital cost for a best-case scenario of $1,500/kW and a worst-case scenario of $3,000/kW. The simulation results shown in Figure 3-18 indicate that the NPV of a NaS installation for providing energy arbitrage and synchronized reserve is positive only for the lowest capital cost estimate of $1,500 /kW. For the average cost estimate of $2,000 / kW the NPV is negative for 100% of the simulations. The mean NPV for the lowest cost estimate is approximately $350,000. The mean NPV for the average cost estimate ($2,000/kW) is -$140,000. For the highest cost estimate ($3000/kW) of a NaS battery installation, the mean NPV drops to -$1,100,000.

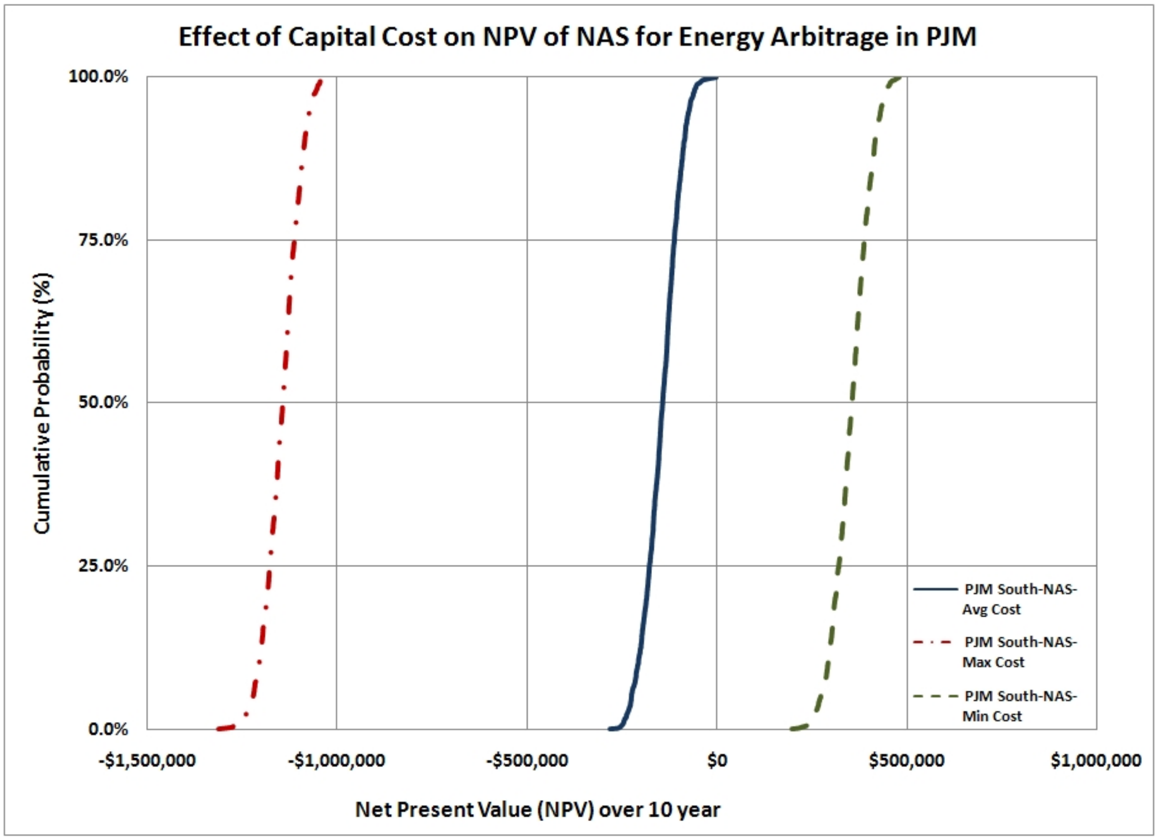

Figure 3-18. Effect of Capital Cost on NPV of NaS for Energy Arbitrage in PJM South

For the PJM South region, that offered the maximum revenue potential for a NaS battery, a sensitivity analysis was performed to evaluate the effect of round-trip efficiency on the NPV of a NaS installation. The results shown in Figure 3-19 indicate that even with the best-case scenario of 85% round-trip efficiency, there is only a 2.3% probability of a positive NPV for a NaS installation. The mean NPV for round-trip efficiency of 85% is -$80,000, that drops to -$230,000 for a NaS battery with round-trip efficiency of 65%.

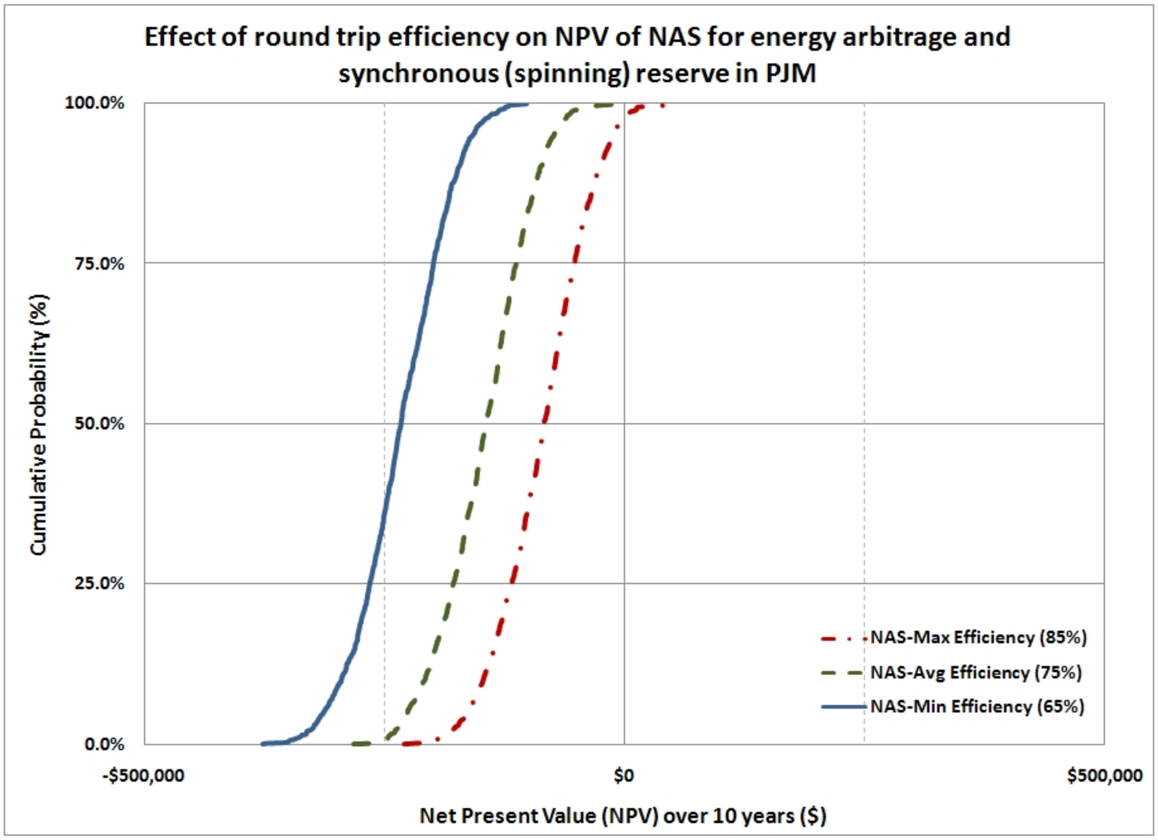

Figure 3-19. Effect of Round-Trip Efficiency on NPV of NaS for Energy Arbitrage in PJM South for Average Capital Cost

Figure 3-20 compares the NPV of a flywheel installation for regulation with the NPV of a NaS battery for energy arbitrage and synchronized reserves. These results indicate that unless the NaS installation cost drops below $2,000 /kW or there is a scenario where the NaS installation is able to generate additional benefits of more than $150,000 /MW-yr, there is no economic case for NaS in PJM for the average capital cost estimate. The current installation of a NaS battery by AEP at Charleston, West Virginia, is such an example, where AEP made a decision to invest in the NaS battery based on deferring substation upgrade costs of $2,000/kW. AEP plans to move the NaS battery after 2-3 years of field operation to different substations to maximize the savings in deferring the costs of upgrading substations. (Nourai 2006).

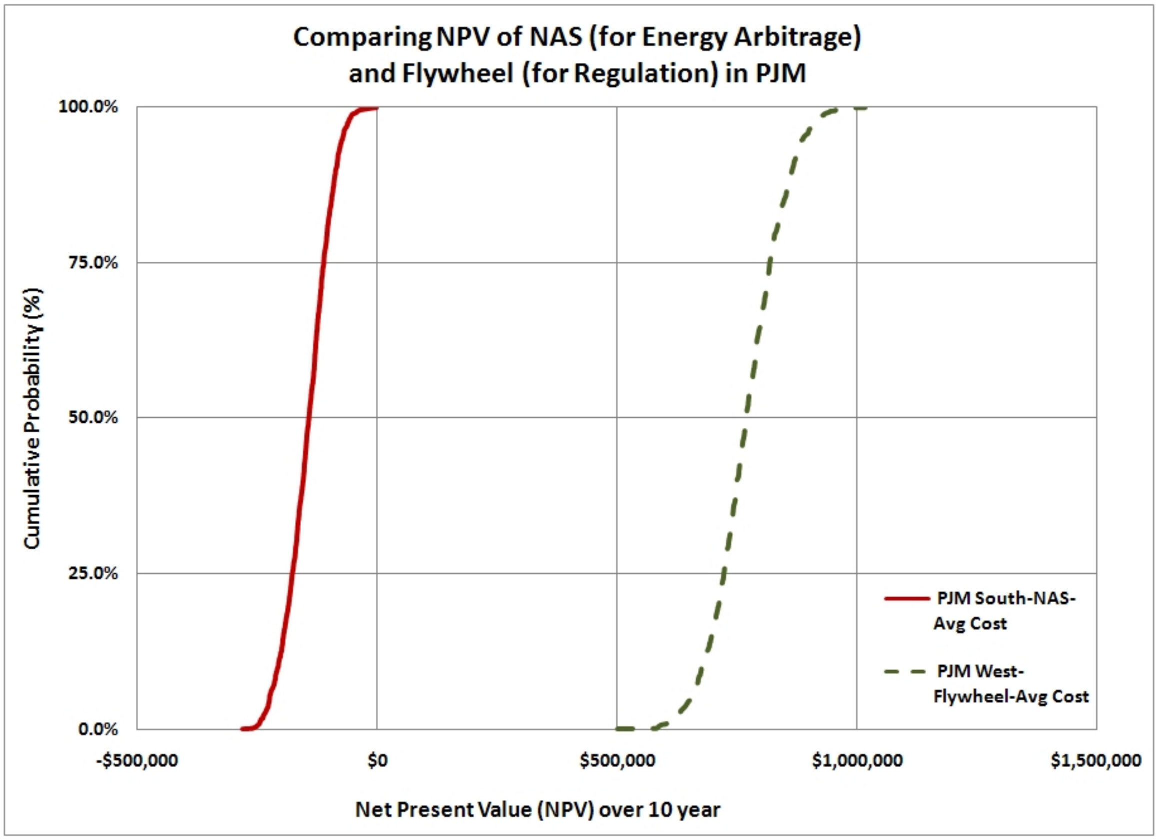

Figure 3-20. Comparison of NPV of NaS for Energy Arbitrage (PJM-South) and Flywheel for Regulation (PJM West) Using the Respective Average Capital Costs

3-8. Comparing the Economics of EES in NYISO and PJM

This section provides a summary comparison of the NPV analysis of NaS batteries and flywheels for the NYISO and PJM electricity markets. The comparison is provided by using the base case scenarios using the average capital cost for both technologies. For regulation, market results for NY West and PJM West regions were used as these regions offer the maximum net revenues for regulation in respective markets. For energy arbitrage, market results from NYC and PJM South regions were used for the same reason. The results are shown in Figure 3-21, 3-22 and 3-23.

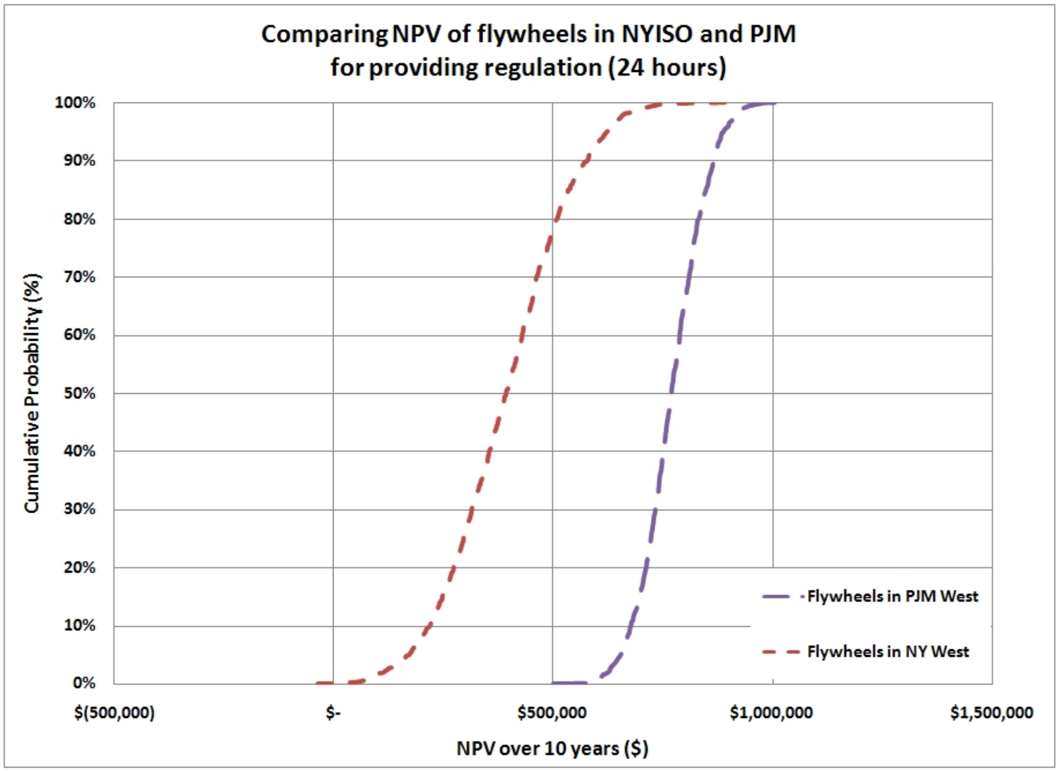

Figure 3-21. Comparison of NPV of Flywheel for Regulation in NYISO and PJM for Average Capital Costs

Figure 3-21 indicates that the mean NPV of flywheels for providing regulation is positive in both NYISO and PJM. There is a 50% probability that NPV for flywheels will be approximately $390,000 in NYISO's NY West region and $770,000 in PJM in the PJM West region.

A similar comparison of the NPV of NaS batteries for providing 4 hour energy arbitrage and 15 hours of synchronized reserves in NYISO (NYC region) and PJM (PJM South region) indicates that then mean NPV for both markets is negative. The mean NPV for NaS batteries in NYC is -$150,000 and -$140,000 in PJM South. The energy arbitrage revenue in NYISO has a larger uncertainty due to higher volatility in energy prices. There is a 2% probability of NaS batteries achieving a positive NPV in NYC region, whereas in PJM the NPV remained negative in all 1000 iterations.

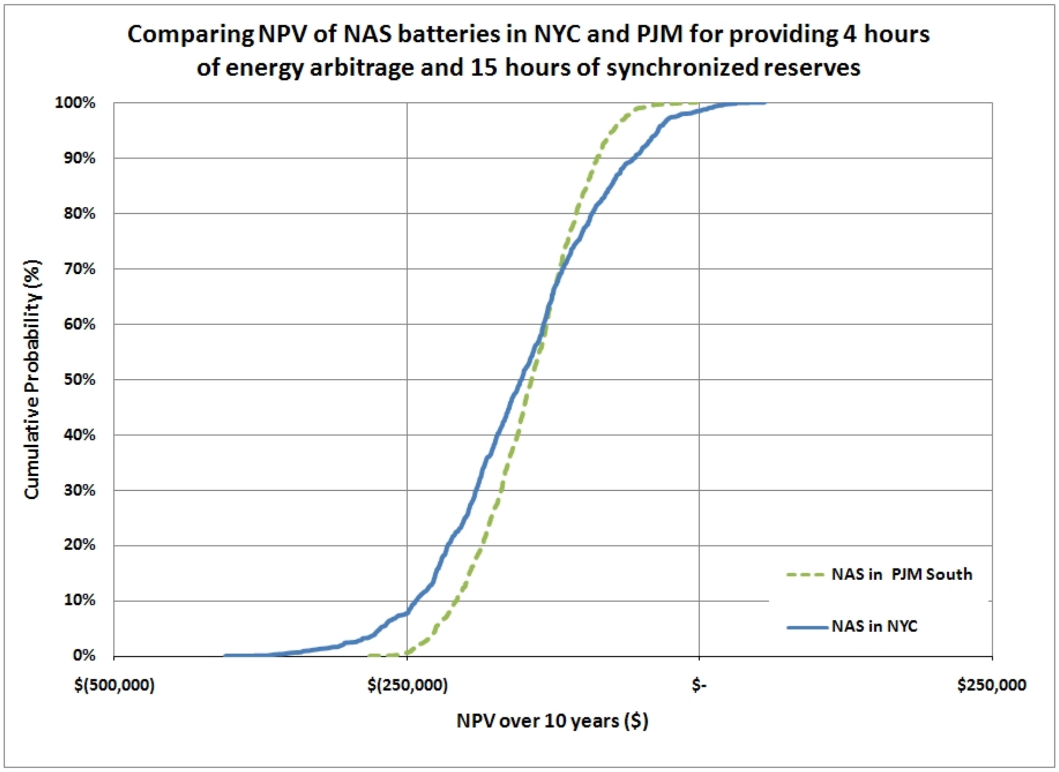

Figure 3-22. Comparison of NPV of NaS Batteries for Energy Arbitrage and Synchronized Reserve in NYISO and PJM

Figure 3-23 provides a comparison of NPV of flywheels for regulation with NPV of NaS batteries for energy arbitrage and synchronized reserves in both PJM and NYISO markets.

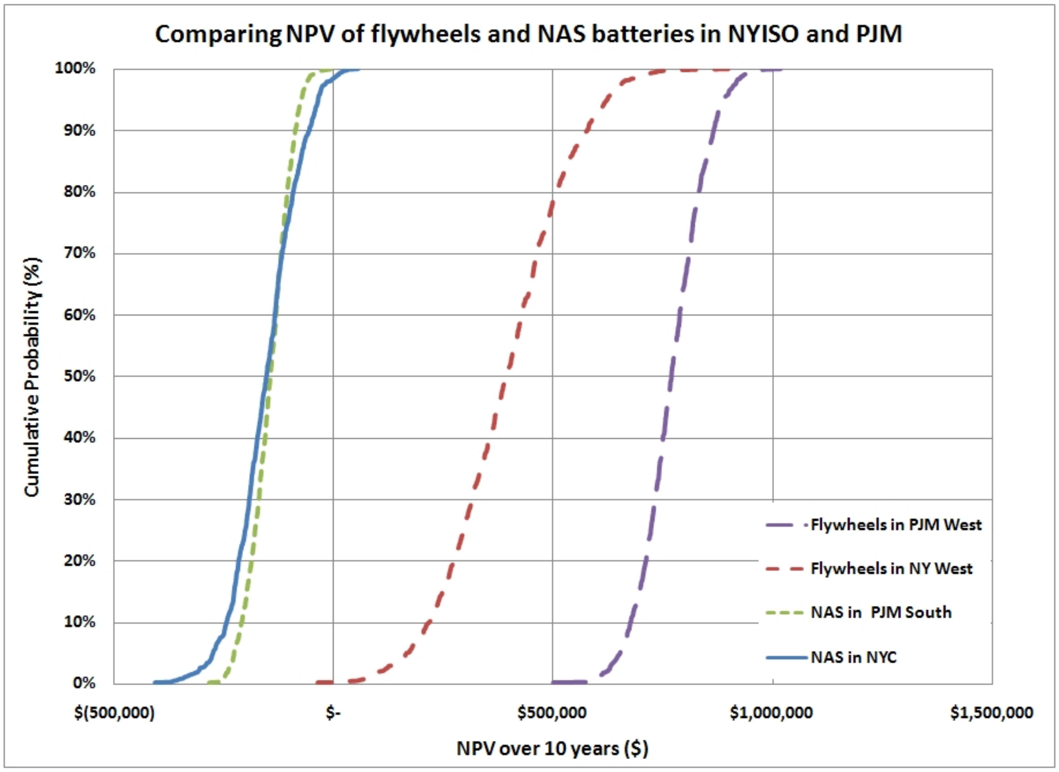

Figure 3-23. Comparison of NPV of Flywheels and NaS Batteries in NYISO and PJM

3-9. Conclusions: EES in PJM

Similar to NYISO markets, PJM markets allow EES technologies to participate in the electricity markets. This research covered evaluation of flywheels for providing regulation, and NaS batteries for providing energy arbitrage and synchronized reserves in various PJM regions. Based on the current analysis of market data from 2005-2007, the regulation market offers the best opportunity for flywheels despite some uncertainties due to the energy-limited nature of flywheels.

There could be a substantial change in regulation revenues that can be captured by flywheels, if the regulation market rules are modified to address two issues discussed above: the effect of potential regulation performance criteria on limited energy availability of flywheels and the treatment of opportunity costs paid to traditional generators that can suppress the regulation market clearing prices in PJM. The sample regulation signal provided by PJM suggests that flywheels may be able to provide regulation for less than 60% of the duration. Although under current market regulations, flywheels are eligible to receive full regulation revenues, if PJM decides to pro-rate the payment based on the availability of a regulation unit, this could lower the regulation revenues significantly. On the other hand, if PJM allows flywheels to receive additional payments similar to opportunity cost payments received by traditional generation units used for regulation, then the revenue potential could be significantly higher.

Our analysis indicates that, although current policies allow emerging EES technologies to participate in energy markets for capturing energy arbitrage opportunities, changes in some of the ancillary service-related policies can reduce financial and regulatory uncertainty for EES. While the primary barriers to EES penetration are economic, in both PJM and NYISO changes to current market rules and reliability criteria could permit EES to participate in the synchronous spinning reserve market and reduce the current uncertainty in regulation market rules.

- Market rules should be changed to resolve uncertainty related to the energy limited nature of EES in regulation markets. NYISO is currently considering a rule change that would mandate a response rate of greater than 90% from regulation units, which could result in disqualification of energy limited EES such as flywheels (which may have as much as 40% idle time based on the nature of the regulation signal). If adopted, this rule would inhibit the adoption of flywheels. The market rules for regulation should recognize the limited energy availability as well as faster response time provided by energy storage technologies. This would require that the regulation signal sent to these devices be customized to ensure that units such as flywheels are not sitting idle due to their energy limited nature. The California ISO is currently evaluating such an option to introduce a separate category of regulation services through fast response energy storage technologies.
- Our analysis indicates that the case for EES to participate in regulation market could be further enhanced if the opportunity costs paid to traditional generators are captured as part of the regulation market clearing price (RMCP) in PJM. PJM is considering changes to the RMCP payment that may include EES.
- The current market rules related to synchronized reserves permit that the service can be provided by generators synchronized to the grid operating on no load. Thus although EES can meet the technical requirements of synchronized reserves, the market rules should ensure that EES is eligible to receive synchronous reserve payments, by making reserve payments technology independent. PJM has already modified market rules to allow demand response participation in the ancillary service markets and NYISO is currently working on similar modifications; EES should receive similar consideration.

The analysis of PJM market data from 2005-2007 indicates that current market-based revenue streams are not sufficient to justify investment in NaS batteries for energy arbitrage and synchronized reserves in any of the PJM regions covered in this study. This analysis indicates that capital cost reduction is one of the major improvements required for NaS batteries to become economical for providing energy arbitrage in PJM. It is also important not to sacrifice efficiency as a means for reducing the capital cost, as lower round-trip efficiency will reduce the net revenue potential from energy arbitrage.

However even with the lack of clear positive NPV for NaS batteries, market participants may invest in such installations if it is possible to combine the market based revenues with traditional benefits offered by EES as shown by the sensitivity analysis in appendix 2-A-4. AEP has justified the investment in the 1.2 MW, NaS battery installation at Charleston, WV based on the anticipated savings in substation upgrade deferral. AEP expects to utilize the NaS battery to defer a capital investment of $2000/kW in substation upgrade. (Nourai, 2006) AEP also has plans to install a 2 MW NaS battery near Milton, W.Va., to enhance reliability and allow for continued load growth in that area. AEP is planning to install a 2 MW NaS battery unit near Findlay, Ohio, to enhance reliability, provide support for weak sub-transmission systems, and avoid equipment overload. (AEP, 2007).

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Appendix 3-A-1. Distribution of Zonal LMP prices

Appendix 3-A-1 shows the summary of the statistical analysis of zonal LMP prices for 17 PJM zones for different periods: the complete year, the summer capability period, and the winter capability period based on 2005-2007 data. For PJM's operations the on-peak period is defined as hours between 7:00 am and 11:00 pm (prevailing Eastern Time) on non-holiday weekdays. The off-peak period is defined as are all those hours not defined as on-peak i.e. hours between 11:00 pm and 7:00 am (prevailing Eastern Time) on weekdays and all day Saturday, Sunday and NERC defined holidays. The summer capability period is defined as May 1st through October 31st and the winter capability period as November 1st through April 30th.

Table 3-A 1. Regional Distribution of Peak LMP Prices ($/MWh) for 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$73.35	$58.32	$68.95
	PENELEC	$71.57	$56.77	$66.54
PJM East	AECO	$88.76	$68.16	$78.04
	DPL	$85.23	$65.31	$76.17
	JCPL	$84.34	$63.44	$78.54
	METED	$82.25	$65.31	$76.43
	PECO	$85.16	$64.60	$75.22
	PPL	$81.31	$63.54	$74.03
	PSEG	$87.11	$66.33	$79.41
	RECO	$83.57	$66.14	$78.83
PJM South	BGE	$83.41	$67.26	$80.18
	DOM	$90.75	$64.95	$76.66
	PEPCO	$85.03	$68.59	$81.03
PJM West	AEP	$61.82	$51.91	$59.45
	COMED	$61.24	$51.73	$59.55
	DAY	$60.51	$50.85	$59.11
	DUQ	$58.12	$48.72	$57.04

Table 3-A 2. Regional Distribution of Peak LMP Prices ($/MWh) for the Summer Capability Period 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$73.35	$58.32	$68.95
	PENELEC	$71.57	$56.77	$66.54
PJM East	AECO	$88.76	$68.16	$78.04
	DPL	$85.23	$65.31	$76.17
	JCPL	$84.34	$63.44	$78.54
	METED	$82.25	$65.31	$76.43
	PECO	$85.16	$64.60	$75.22
	PPL	$81.31	$63.54	$74.03
	PSEG	$87.11	$66.33	$79.41
	RECO	$83.57	$66.14	$78.83
PJM South	BGE	$83.41	$67.26	$80.18
	DOM	$90.75	$64.95	$76.66
	PEPCO	$85.03	$68.59	$81.03
PJM West	AEP	$61.82	$51.91	$59.45
	COMED	$61.24	$51.73	$59.55
	DAY	$60.51	$50.85	$59.11
	DUQ	$58.12	$48.72	$57.04

Table 3-A 3. Regional Distribution of Peak LMP Prices ($/MWh) for the Winter Capability Period 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$64.67	$54.73	$65.01
	PENELEC	$62.82	$54.79	$64.43
PJM East	AECO	$75.19	$63.57	$71.36
	DPL	$72.95	$61.53	$71.81
	JCPL	$73.98	$60.56	$77.01
	METED	$68.32	$61.02	$71.30
	PECO	$71.71	$61.21	$70.94
	PPL	$68.02	$60.73	$70.55
	PSEG	$75.11	$63.41	$77.11
	RECO	$72.35	$63.69	$78.07
PJm South	BGE	$68.00	$62.61	$73.43
	DOM	$85.50	$59.80	$71.03
	PEPCO	$68.91	$62.50	$74.14
PJM West	AEP	$56.42	$50.00	$56.04
	COMED	$55.71	$49.65	$56.04
	DAY	$55.64	$49.22	$55.71
	DUQ	$55.40	$47.06	$53.26

Table 3-A 4. Regional Distribution of Off-Peak LMP Prices ($/MWh) for 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$44.87	$37.82	$42.60
	PENELEC	$43.81	$36.84	$41.12
PJM East	AECO	$51.67	$42.83	$49.79
	DPL	$51.22	$42.32	$49.55
	JCPL	$49.61	$40.67	$49.78
	METED	$49.78	$41.67	$48.69
	PECO	$50.75	$41.96	$49.05
	PPL	$49.16	$41.05	$47.76
	PSEG	$52.39	$42.74	$50.44
	RECO	$51.25	$42.81	$49.88
PJM South	BGE	$52.47	$45.35	$52.46
	DOM	$54.73	$45.62	$51.86
	PEPCO	$53.60	$46.55	$53.70
PJM West	AEP	$35.92	$32.29	$33.42
	COMED	$34.48	$31.80	$32.96
	DAY	$34.91	$31.22	$33.24
	DUQ	$33.92	$30.52	$32.15

Table 3-A 5. Regional Distribution of Off-Peak LMP Prices ($/MWh) for the Summer Capability Period 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$44.87	$37.82	$42.60
	PENELEC	$43.81	$36.84	$41.12
PJM East	AECO	$51.67	$42.83	$49.79
	DPL	$51.22	$42.32	$49.55
	JCPL	$49.61	$40.67	$49.78
	METED	$49.78	$41.67	$48.69
	PECO	$50.75	$41.96	$49.05
	PPL	$49.16	$41.05	$47.76
	PSEG	$52.39	$42.74	$50.44
	RECO	$51.25	$42.81	$49.88
PJM South	BGE	$52.47	$45.35	$52.46
	DOM	$54.73	$45.62	$51.86
	PEPCO	$53.60	$46.55	$53.70
PJM West	AEP	$35.92	$32.29	$33.42
	COMED	$34.48	$31.80	$32.96
	DAY	$34.91	$31.22	$33.24
	DUQ	$33.92	$30.52	$32.15

Table 3-A 6. Regional Distribution of Off-Peak LMP Prices ($/MWh) for the Winter Capability Period 2005-2007

Region	Zone	2005	2006	2007
PJM Central	APS	$45.17	$40.06	$44.73
	PENELEC	$43.61	$38.92	$43.43
PJM East	AECO	$50.64	$44.51	$51.69
	DPL	$50.55	$44.48	$52.32
	JCPL	$50.09	$43.22	$53.90
	METED	$49.01	$44.18	$51.58
	PECO	$49.94	$44.17	$51.80
	PPL	$48.49	$43.62	$50.96
	PSEG	$50.73	$44.87	$53.18
	RECO	$49.60	$44.90	$52.53
PJm South	BGE	$50.91	$47.73	$55.36
	DOM	$62.41	$47.46	$54.64
	PEPCO	$51.79	$48.66	$56.66
PJM West	AEP	$36.80	$33.86	$34.94
	COMED	$34.29	$32.91	$34.44
	DAY	$35.80	$32.27	$34.54
	DUQ	$34.64	$31.21	$33.72

Appendix 3-A-2. Determining Operating Hours for Energy Arbitrage

Appendix 3-A-2 shows the results of the analysis performed to determine the operating hours for 4-hour energy arbitrage in each of the 4 super-zones.

Figure 3-A-1 shows the distribution for the 4 hour maximum revenue period during summer capability period during 2005 and 2006 for all 4 super zones. During the summer capability months the 4 hour period is 15:00 to 18:00.[9] The most common period for maximum revenue The maximum revenue period for 4 hour energy arbitrage operations shift to period ending at 18:00 (i.e. from 5:00 pm) during the winter capability period as shown in Figure 3-A-2. The least cost period used for charging the EES during the 4 hours energy arbitrage operations does not show such seasonal shift. Figure 3-A-3 shows that the minimum cost period for all regions during the year is 2:00 to 5:00.

[9] PJM uses the convention of hour ending with. Thus hour 15:00 refers to hour ending at 15:00 i.e. hour that began at 14:00:01.

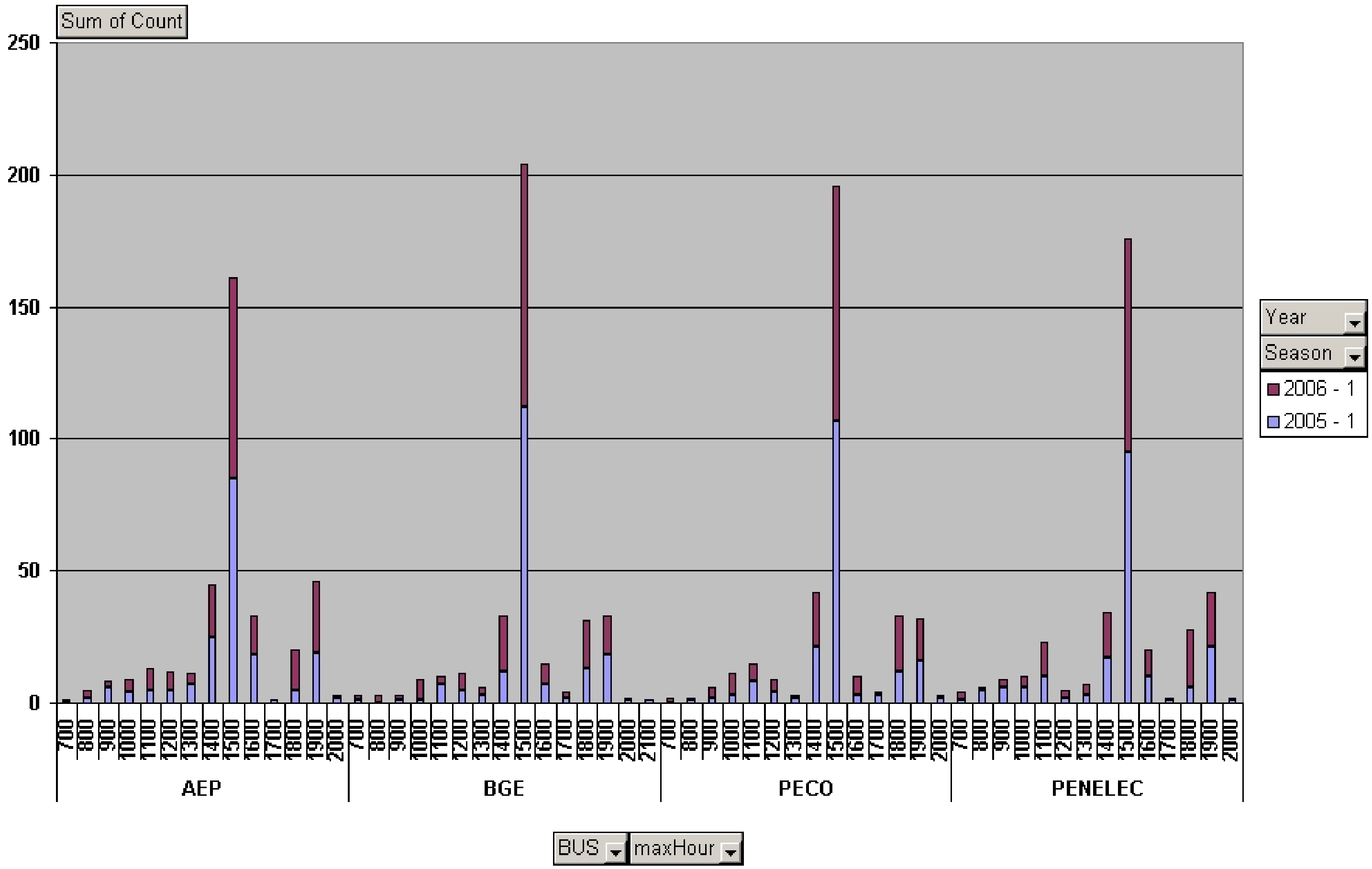

Figure 3-A 1. 4-Hour Maximum Revenue Period During Summer Capabilities Months (i.e. May – October)

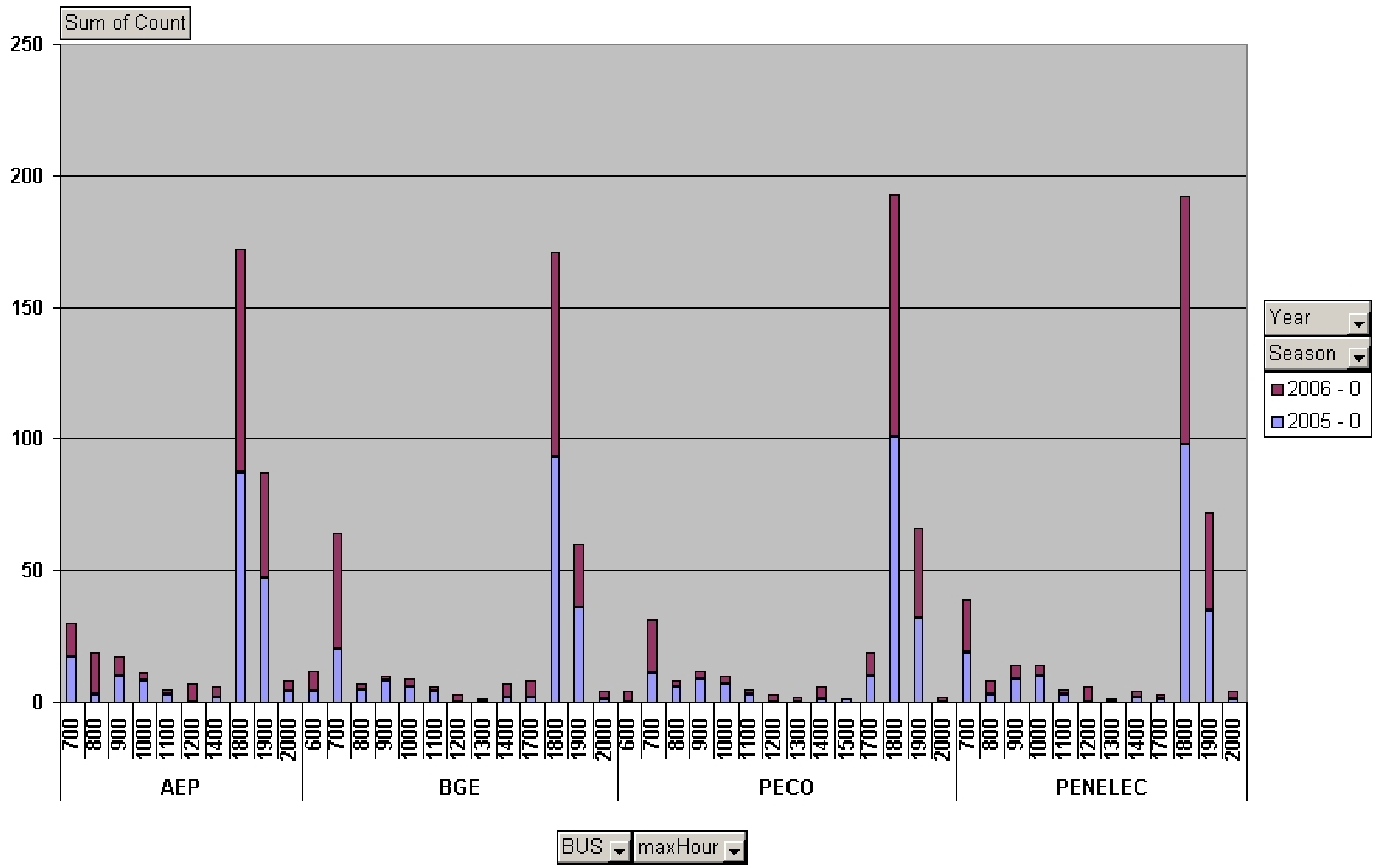

Figure 3-A 2. 4-Hour Maximum Revenue Period During Winter Capabilities Period (i.e. November – April)

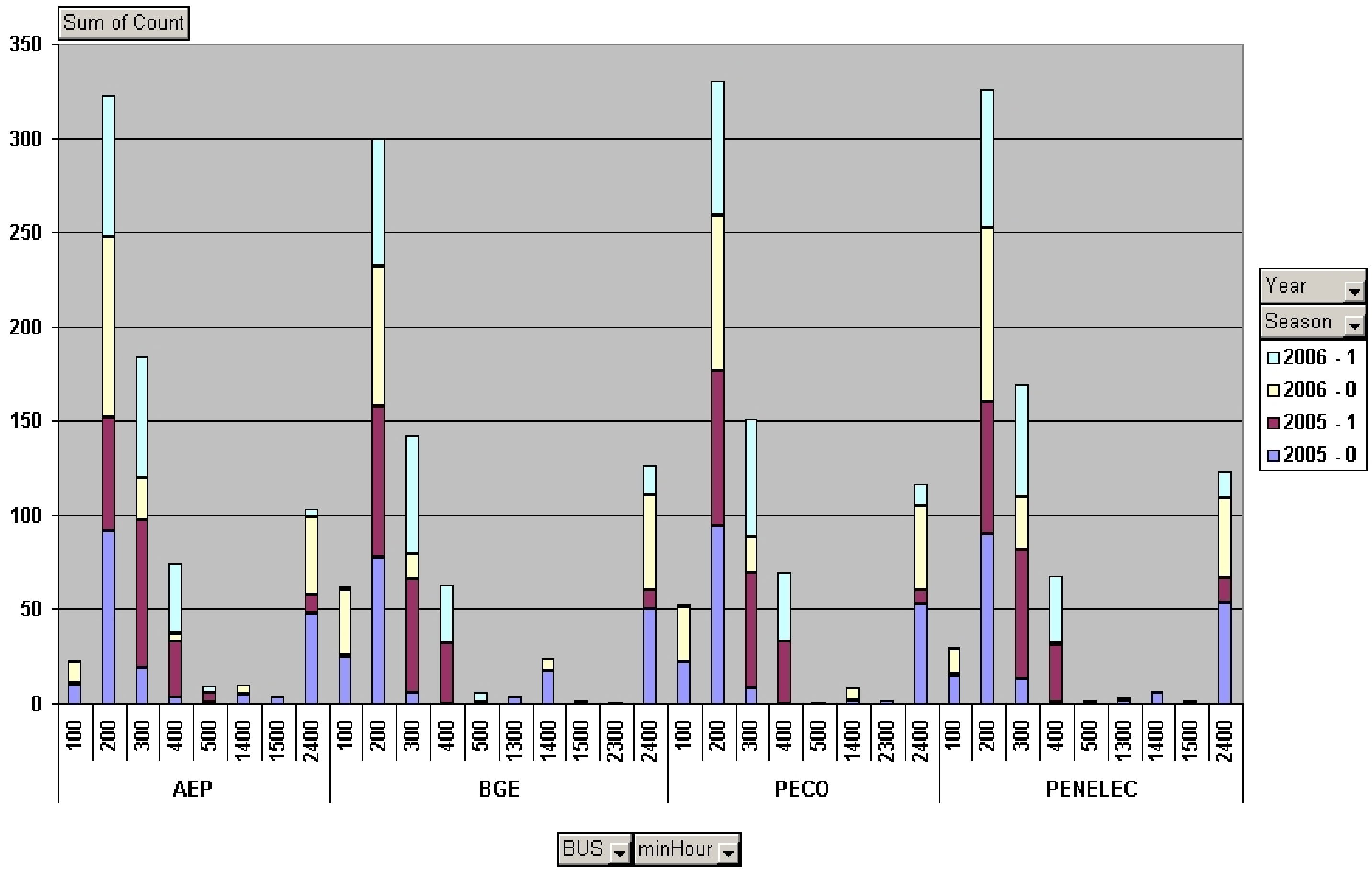

Figure 3-A 3. 4-Hour Minimum Charging Cost Period During Complete Year (Includes Both Summer and Winter Capabilities Periods)

Appendix 3-A-3. Sensitivity Analysis for Financial Input Parameters of NPV for NaS Batteries for Energy Arbitrage

We performed a sensitivity analysis to determine the most important factors influencing the economics of NaS batteries for energy arbitrage in the PJM South region. Table 3-A-7 summarizes the range of input parameters used for the sensitivity analysis.

Table 3-A 7. Range for Financial Parameters Used for Sensitivity Analysis

Input Variable	Low	Base	High
T&D Benefits ($/kW-Year)	$0	$150	$300
Capital Cost ($/kW)	$1,500	$2,000	$3,000
Annual Revenues ($/MW)	$200,000	$235,000	$280,000
Charging Cost ($/MW)	$45,000	$52,000	$60,000
O&M Costs ($/kW-Year)	$20	$30	$50
Efficiency	65%	75%	85%
Discount Factor	5%	10%	15%

The base case had a NPV of -$238,000. Figure 3-A-4 shows the results of the sensitivity analysis as a tornado plot. Each bar indicates the variability in the NPV as a result of changing an individual factor. For example, the NPV will increase from -$238,000 to $680,000 if the installation can be used at a location that offers T&D benefits of $300 / kW-Year. Also the NPV will increase to $260,000 as compared to the base case if the capital cost is reduced to $1,500 /kW from the base case assumption of $2,000/kW.

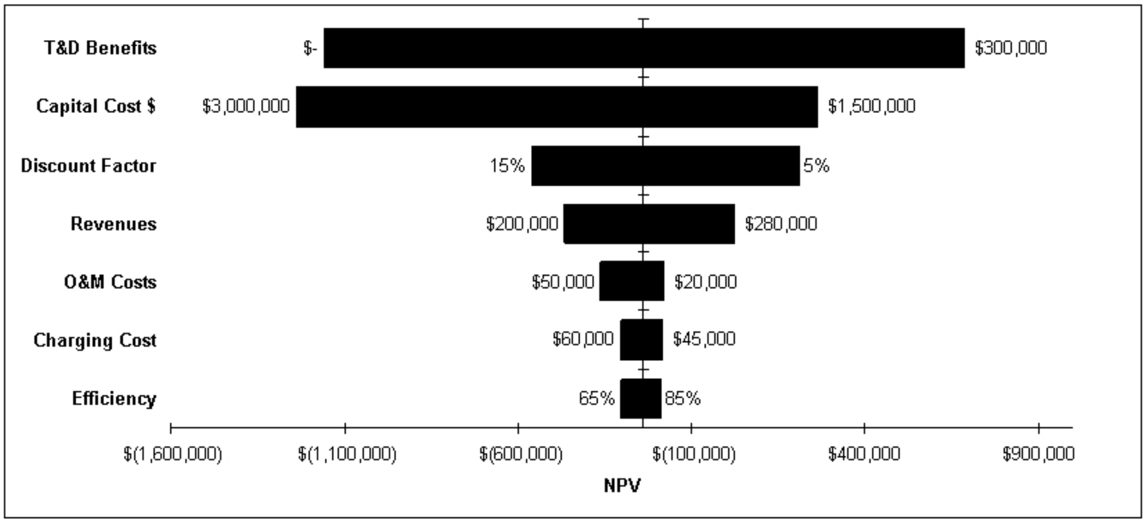

Figure 3-A 4. Sensitivity Analysis for The Net Present Value (NPV) of a NaS Installation for 4 Hours Energy Arbitrage in PJM South